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Wright-Patterson Air Force Base, Ohio

PRODUCTIVITY MEASUREMENT IN
RESEARCH AND DEVELOPMENT LABORATORIES

Thomas A. Fauth, Captain, USAF

LSSR 87-81

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This investigation into the measurement of productivity of research and development (R&D) laboratories consisted of an exhaustive theoretical and empirical literature search and an extensive telephone interview process to identify the state-of-the-art R&D productivity indicators. The literature search (of publications from 1960 to the present) resulted in a chronological presentation of theoretical and empirical R&D productivity measurement methodologies and an expanded bibliography. The telephone interview process surveyed 14 Air Force, 30 Army, 20 Navy, and 21 industry laboratories. Specific literature and interview objective and subjective R&D productivity measurement indicators were identified and compared. Both objective and subjective productivity indicators were identified as the primary means of measuring laboratory productivity in the literature (empirical combined government and industry - 59% theoretical combined government and industry - 46%) and from the interviews (government - 92%, industry - 62%). Status versus milestones, the degree technical objectives are reached, expenditures versus budget, and periodic reviews were the most common (of a standardized list of 18) indicators to both government and industry laboratories. Effectiveness is perceived as a more important component of productivity than efficiency is.

LSSR 87-81

PRODUCTIVITY MEASUREMENT IN RESEARCH AND DEVELOPMENT LABORATORIES

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Management

By

Thomas A. Fauth, BA
Captain, USAF

September 1981

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Capt Thomas A. Fauth

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS MANAGEMENT

DATE: 30 September 1981

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READER

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CHAPTER 1

INTRODUCTION

> Although we cannot measure it precisely, research and development activity is our best indication of the investment in the scientific and technological advance that sooner or later results in productivity growth [36:10].

Productivity growth on the national level has been defined as ". . . the increase in goods and services produced per hour of work . . . (11:xiii)." The January 1981 Congressional Budget Office report identifies innovation (technological progress) as one of the five long run determinants of productivity growth (11:2-3). Simply put, productivity growth is the ". . . rate of growth in real income per capita - in the standard of living (48:3)." But before natural productivity growth can be determined, productivity measurement systems must exist and be used in the vast number of industries and government. Man-hours, tonnage, volume, distance, services, facilities, dollars, and various ratios thereof are commonly used measures of inputs and outputs annually reported tc indicate industrial, and ultimately national productivity.

The major source of government productivity measures is the Bureau of Labor Statistics. Official productivity measures are obtained from separate and independent surveys

that are conducted to determine information for purposes other than for productivity measurement. Measures for specific industries are published only when the data permit relatively good measures (48:51-53).

> The Department of Defense (DoD) supports between one-third and one-fourth of all the scientists and engineers in the United States, and has commensurate power in influencing the types of research to be performed and the products to be developed. Over half of the approximately $40 billion spent in the United States each year on research and development comes from the federal government, and of this national defense accounts for more than half.
>
> This $10 billion or more spent yearly by the Department of Defense is not by itself what makes defense research and development so critically important. Rather, it is the fact that the United States bases its overall defense posture almost entirely on "technological superiority" that makes R&D (Research and Development) a central focus for the DoD and therefore for the defense industrial base.

This large annual dollar expenditure on R&D, the concept of technological superiority, and the importance of technological progress as a determinant of productivity growth begs investigation into the measurement of government and industry R&D productivity.

Background

Interest in the measurement of R&D laboratory productivity grew from the investigator's four years of research experience gained with Rome Air Development Center's Electronic Technology Division (RADC/ET). Exposure to Research, Development, Testing, and Evaluation (RDT&E), the progressive phases of the R&D process in DoD, launched this

inquiry into performance measurement, and in turn productivity measurement of the five main categories of DoD laboratory responsibility defined in Table 1-1 (17:INTRO-21). Mansfield defines the terms "research" and "development" in a simpler manner as follows:

> "Research" is original investigation directed to the discovery of new scientific knowledge, and "development" is technical activity concerned with nonroutine problems encountered in translating research findings into products and processes. . . . Whereas research is conducted to obtain new knowledge, development is required to reduce the knowledge to practice. This often entails the making of various types of experiments, the design and development of prototypes, and the construction of pilot plants [43:6-7].

Similarly, Seiler states "Basic research obviously contributes new knowledge, applied research connects this knowledge with one or more specific products, and development prepares these products for manufacture (58:187)." Others express essentially the same ideas (2:12; 55:3-4) indicating industry and government share common terminology.

The 14 Air Force Laboratories, 34 Army Laboratories, and 22 Navy Laboratories listed in Appendix A are all involved in one or more of these five laboratory responsibilities in the form of in-house programs, contractual efforts, or both. The initial objective of this research effort was to survey all Air Force Systems Command (AFSC) laboratories in order to:

1. Define the units of productivity.
2. Identify the variables affecting productivity.
3. Determine the feasibility of adapting procurement productivity indices to the R&D laboratory.

TABLE 1-1

DOD RESEARCH AND DEVELOPMENT CATEGORY DEFINITIONS

1. Research - The initial laboratory purpose is to identify and develop a knowledge base. This category includes fundamental investigation toward the increased understanding of natural phenomena and the environment. It encompasses an attempt to find solutions in the physical, behavioral, and social sciences. It normally does not present a clear or direct military application.

2. Exploratory Development - This phase embodies efforts toward the solution of specific military problems, but excludes major development. Primarily, laboratory experts explore and develop a technological base and evaluate the practicability and feasibility of proposed solutions.

3. Advanced Development - When a technological base has been achieved, projects are moved into this phase using and creating hardware for experimental or operations tests. At this point, technologies are combined to become a stage for some actual production, although usually tested items are not released for service or general use.

4. Engineering Development - This is usually the prototype stage in which a design is geared for service use. Systems emerge at this level, and items undergo extensive performance testing.

5. Management and Support - This category refers to work directed toward the support of installations and/or operations required for general R&D use. The goal, from this perspective, is to obtain operational capability through general support.

4. Measure laboratory performance against predetermined goals.

5. Measure a laboratory's productivity against itself over time and against other laboratories' productivity.

6. Develop a model to predict laboratory productivity.

Further investigation into these six objectives and meeting with AFSC personnel indicated they could not be accomplished in the time period available to the investigator, but they remain as potential long-term objectives for future studies. The objectives of this research effort then evolved to the following:

1. Conduct an extensive literature review of public and private publications to determine the evolution of R&D productivity measurement from 1960 to the present (state-of-the-art).
2. Determine the qualitative and quantitative measures of productivity, theoretical and empirical.
3. Identify the prevalent variables affecting productivity.
4. Identify literature similarities, contradictions, and novelties.
5. Interview Industry and DoD laboratories to determine/identify currently used productivity measurement techniques and variables, if any.

Definitions

This investigation into the measurement of productivity in R&D laboratories requires that a consistently defined and applied set of terms be included for clear comprehension. The terms are defined in Table 1-2 and retain their definitions throughout this thesis. The terms productivity, efficiency, and effectiveness were also verbally defined during each laboratory telephone interview to maintain commonality in word meaning between each laboratory.

TABLE 1-2

PRODUCTIVITY DEFINITIONS

1. PRODUCTIVITY: "The productivity of an organization may be broadly defined as the efficiency with which its resources are utilized to produce final outputs (53:4)." Productivity is a product of efficiency and effectiveness. In equation form

   PRODUCTIVITY = PERFORMANCE/RESOURCES
   = DIRECTED OUTPUT/INPUT

   PRODUCTIVITY IMPROVEMENT = INCREASE OUTPUT/GIVEN INPUTS
   or
   = GIVEN OUTPUT/DECREASED INPUTS
   or
   = INCREASED OUTPUT/DECREASED INPUTS

2. EFFECTIVENESS: "Effectiveness concerns the extent to which government programs achieve their objectives (53:5)." Effectiveness identifies the degree to which the laboratory accomplishes its mission.

3. EFFICIENCY: Efficiency refers to the ratio of output to input and implies "more, better, faster and cheaper . . . (1:13)." Efficiency concerns the utilization of resources to execute laboratory programs and functions at minimal cost (53:5).

4. OBJECTIVE MEASURES: Objective measures are quantifiable resources and performance measures. These measures may be direct or indirect.

5. SUBJECTIVE MEASURES: Subjective measures are qualitative determinants of resource utilization and performance.

6. INVENTION: Invention is "the creation of an idea and its reduction to practice; the first stage of innovation (2:8)." Invention "aims at the practical application of a principal which may be fully or only partially apprehended (55:4)."

7. INNOVATION: Innovation is "the bringing of an invention into widespread, practical use (2:8)," and the "change with respect to existing practices (70:35)."

8. CREATIVITY: Creativity is "the process in which either original or imaginative ideas are conceived or communicated (47:873)."

To properly determine productivity in an R&D laboratory, productivity indicators must either directly or indirectly, and objectively or subjectively, measure laboratory inputs (budget, man-hours, mental activity. . .) and outputs (papers, contracts, briefings, patents. . .). Objective information is more desirable than subjective information because quantified information lends itself to comparison and reduces prejudicial distortion. The phrase "directed outputs" (performance) is preferred over the term outputs because it specifically indicates performance directed toward an R&D objective rather than just the accomplishment of some task or service. Good measures should incorporate the concepts of reliability, consistency, stability, and validity, as identified by Szilagyi and Wallace (67:447-453), because these concepts "refer to the adequacy of the information that is generated and employed in subsequent decisions. . . (67:449)." The reference pertains to individual performance measurement, but is directly applicable to the performance measurement of an R&D organization.

The terms inventions, innovation, and creativity are frequently associated with scientific output, and are therefore included in Table 1-2. The definitions indicate the difficulty of formulating indicators to measure these types of outputs. Invention disclosures and patents may indicate the quantity of output, but a subjective determination of the

quality of the invention disclosures and patents should also be made, which does not easily lend itself to comparison with other invention disclosures and patents. Widespread implementation of a medical diagnostic technique is an example of an innovation, but time is the critical factor. How widespread is widespread, and how much change is required? Either response is still most likely several years removed from the initial invention. The communication of original ideas is easier to measure than the process of idea conception, but the subjectivity problem recurs. These examples clearly indicate the types of problems which must be dealt with in measuring R&D productivity.

Statement of the Problem

This seeming dilemma has given rise to the need to identify qualitative and quantitative factors measuring productivity in public and private R&D laboratories. An effective measure of productivity has not been identified because common measures for laboratory productivity have not been defined. This problem exists because of the task characteristics unique to the laboratory research and development function; i.e., protracted work cycles and the absence of an identifiable product.

Scope and Limitations

This study examines the theoretical and empirical publications concerning the collective productivity

measurement of scientists, engineers, and their managers, and determines current laboratory perceived productivity indicators used to measure productivity in DoD and selected industry laboratories. The types of R&D laboratory personnel investigated include chemists, physicists, engineers, technicians, metallurgists, logisticians, work effort leaders, and branch chiefs. Specifically not included are administrative (secretarial) employees and high level laboratory managers.

This thesis is limited to the study of R&D productivity measurement. Productivity improvement, productivity enhancement, and factors affecting laboratory productivity are not explored, but an expanded Related Sources, contained in the Bibliography section, is included to serve as an initial step for follow-on study of these related topics.

CHAPTER 2

RESEARCH METHODOLOGY

This investigation into the state-of-the-art of productivy measurement in the research and development community consisted of three distinct areas of interest identified as follows:

1. A review of the empirical literature of industry and DoD laboratories.

2. A review of the theoretical literature of industry and DoD laboratories.

3. An extensive telephone interview of industry and DoD laboratories.

These three interests were pursued using two methodologies: an exhaustive search of the theoretical and empirical literature, and an extensive telephone interview process.

Literature Resources

The empirical and theoretical literature reviews were conducted simultaneously using the following four services:

1. Defense Technical Information Center (DTIC);
2. Lockheed Data Log;
3. National Technical Information Service (NTIS);
4. National Referral Center (NRC).

These library and national services provided the majority of all references used. These are limited however for two reasons: first, they are totally dependent on searchers using the proper key words, and secondly, all useful

publications may or may not be entered into the Systems. Text book references were found from the card catalogues at the Wright State University Library, the Air Force Institute of Technology Libraries, and the Wright-Patterson AFB Technical Library. The key words used in the searches are listed in Table 2-1. The term evaluation is not included in the listing because nearly every article located with this key word referred to evaluating alternative research projects prior to laboratory investigation, and did not evaluate completed or on-going research projects.

Additional literature references and information were also obtained from personal telephone interviews (conducted by the author) with recognized experts in the field of productivity measurement. Each publication was classified as theoretical or empirical and was reviewed accordingly. Empirical literature was characterized by a specific sample or population, whereas theoretical publications were not. Many publications contain a combination of significant theoretical and empirical information. R&D productivity measurements are more of an indirect than direct nature. In an effort to specifically identify the most commonly used indicators, specific partial productivity indicators (output/partial input) are pursued rather than a Total Factor Productivity (TFP) measurement (42:40), which is essentially a composite of all partial productivity measurements in common terms.

TABLE 2-1

KEY SEARCH WORDS

DTIC, NTIS, LOCKHEED DATA LOG, NRC	CARD CATALOGUE
Air Force Research	Effectiveness
Army Research	Efficiency
Army Laboratories	Empirical
Industrial Research	Innovation
Military Research	Measures
Naval Research	Performance
Naval Research Laboratories	Productivity
Productivity	Productivity Variables
Research	Reliability
Research and Development	Research
Research Facilities	Research and Development
Research Laboratories	Theoretical
	Variables
	Validity

Telephone Interview

In addition to, and to complement the literature review, original data was collected by the author through an extensive telephone interview effort designed to identify "state-of-the-art" productivity measurement criteria (organizational and individual) as used by both DoD and selected private industry laboratories. The DoD

Laboratories interviewed consisted of those laboratories identified in the publication Department of Defense In-House RDT&E Activities, 30 October 1979 (69:xxv-xxx). DoD laboratory telephone numbers were obtained from the publication Institutional Barriers on DOD Laboratories: A Report of the Ad Hoc Task Group on In-House Laboratories to the Deputy Under Secretary for Research and Advanced Technology (52:14-29). The industry laboratories were selected from the list of participants who attended the April 21-24, 1980 International Conference on Productivity Research in Houston, Texas.

The specific questions are provided in Appendix B. The tabled results and discussion are included in Chapter 4.

CHAPTER 3

CHRONOLOGICAL LITERATURE REVIEW

Background

An exhaustive literature search of the theoretical and empirical publications concerning R&D productivity resulted in the 13 theoretical publications and 41 empirical publications chronologically compiled in Appendix C. Empirical publications are distinguished from theoretical publications by the fact that they are characterized by the study of the behavior of a sample or population.

The theoretical table (Table C-1) includes the date, author(s), title of the publication, data collection methodology, the degree of statistical analysis (if any), the primary type of productivity measurement (subjective, objective, or both), and the primary thrusts of the articles. The empirical table (Table C-2) also includes the date, author(s), title of the publication, data collection methodology, type of productivity measurement (subjective, objective, or both), degree of statistical analysis, subject category, and sample or population size.

Table 3-1 is the key to the tables in Appendix C. The data collection methodology column is self-explanatory. The types of productivity measures used (subjective or objective) were determined based on the definitions given in Table 1-2. The degree of statistical analysis colum refers

TABLE 3-1

KEY TO LITERATURE REVIEW TABLES (APPENDIX C)

DATA COLLECTION METHODOLOGY	TYPE OF PRODUCTIVITY MEASURE	DEGREE OF STATISTICAL ANALYSIS	SUBJECT CATEGORY
Su=Survey or Questionnaire	O=Objective	Co=Complete	G=Government
In=Interview	S=Subjective	M=Model	I=Industry
C=Cases Nondirective Observer		N=None	U=University
F=Field Study, Variable Manipulation, Experimental		P=Percentages or ratios	
LR=Literature Review		SD=Standard Deviation	

to the highest level of analysis from none (0) to Complete (correlations). The Subject Category column included respondents from government, industry, or both government and industry laboratories (personnel). The remainder of this chapter is devoted to summarizing the literature review findings.

Theoretical Review

> The survival of a business depends on performance in eight "key result areas": marketing; innovations; human organizations; financial resources; physical resources; productivity; social responsibility; and profit requirements. Drucker argues that the specific goals in any one of these key result areas will vary from one business firm to another [1:56].

The major barrier to understanding the relationship between organizational setting and scientific development "lies in the difficulty of developing techniques to quantitatively and qualitatively measure scientific output (26:192)." Gordon (26:192) stated in 1963:

> . . . that the use of summaries, in conjunction with the "panel" technique in which eminent authorities in given fields are used to evaluate scientific accomplishment, may provide a practical solution to the problem of qualitatively assessing recent research accomplishment.

The proposed panel technique was used to evaluate medical sociology studies on a ten-point scale in each of the following four criteria:

1. Research problem importance;
2. Research productiveness - the extent to which the research adds to the existing knowledge base from established lines of research; extensions of previous theory;
3. Research innovations - the extent to which the research adds to the existing knowledge base through new lines of research, development of new theoretical statements;
4. Overall significance of the findings.

The results indicate that the technique may provide a solution to the problem of qualitative assessment, but that the technique may not apply to all areas of research.

Villers (71:10) suggested the following three ground rules in 1964 regarding the estimates made by research people of the time and money needed to reach a specific technical goal:

> 1. A reasonable range of variance should be agreed upon when the estimate is submitted to eliminate the temptations to provide for a cushion. In may cases, the estimator may be tempted

to delay final completion to avoid the charge of having provided a cushion.

2. Absolute accuracy should not be expected. As long as the research people are within the anticipated range of variance, their performance should be considered as successful.

3. As soon as the research people discover that they are likely to exceed the expected range of variance, they should report the need for more time and money. Management should expect such requests and accept them without automatically objecting but should look into too frequent requests, which obviously indicate abuses.

Broadwell (6:150) states that:

> Engineering Productivity is a function of satisfaction, both desired and obtained, and is proportional to ability.
>
> . . . The engineer's work varies greatly from the normal measurable productivity-type jobs, however, since much of an engineer's value lies in preventing *work--work that is* not necessary or deferrable. Thought and computations--both necessary and time consuming--by the engineer can often prove that there is a better, and perhaps simpler, way of doing a job, or as has been said, the job may be proven unnecessary altogether. In such cases, little or no production-type work is visible. Certainly no measurable work has been performed.
>
> So we are speaking of a different meaning when we refer to Engineering Productivity. We cannot measure it by any given standard.

A series of graphs are developed to emphasize that satisfaction and ability affect output to a *significant* degree. Engineering output depends on the engineer's ability (the right man in the right job) and the trend of the engineer's satisfaction (is the engineer more or less satisfied now than last quarter in terms of money, time, interrests, and other?). Broadwell states that, "if we skillfully

handle the management responsibilities given to us, we can provide a healthy and productive atmosphere within the engineering organization (6:153)."

In order to refine the meaning of scientific research efficiency, and to identify some specific methods to objectively measure it, Lipetz wrote a book in 1965 based on a doctoral thesis submitted more than six years earlier. (40:x-xi).

> In scientific research, however, it is difficult to state with assurance just what the product should be; hence, it is difficult to know what it is in the performance of research organizations that the administrator should try to measure [40:22].
>
> . . . G. A. W. Bolhm asserts, "Without doubt . . . research is the most difficult of all business operations to measure and control." The apparent non-repetitive nature of the objectives of research organizations suggests to many administrators that a measurable unit of scientific research productivity, if developed, could be valid only within a single organization; and, even there, it could retain its validity for only a short time [40:22].

The investigation of the conclusion that research organizations and research administrative techniques can not be objectively compared is the major objective of Lipetz' work.

A useful measurement must satisfy three criteria:

1. The measurement must be pertinent. The measurement must relate to a problem which is important to the administrator.

2. The measurement must relate to a problem which is recurrent in administration and which makes the comparison of different measurement results meaningful.

3. The measurement must be practical. The processes of making or interpreting the measurement

must not introduce adverse affects on the organization which will outweigh the improvement to be gained from the use of the measurement [40:31].

Lipetz reports the results of several surveys taken in both industrial research organizations by Anthony and Day, and in government-sponsored research organizations in the United States and Great Britain by Hiscocks. The research by these authors indicate ". . . that no satisfactory means for evaluating the effectivness of research are now in use (40:33)," as of 1965.

A majority of the measures used at that time to determine research performance were of the following five types:

1. Measurement of personnel. Counts of the number of personnel on the staff with different degrees of education or responsibility, counts of staff-hours consumed for different degrees of education or responsibility.
2. Measurement of space. Determinations of the amount of building volume or floor space given over to different activities or different types of personnel or equipment.
3. Measurement of capital assets. Determinations of the value of buildings and equipment devoted to different activities or to different types of personnel or service support for different activities or different types of personnel.
4. Measurement of expenses. Determinations of the cost of salaries, supplies, or service support for different activities or different types of personnel.
5. Ratios. Calculations of the ratio of any of the above measurements to any other, e.g., total annual expense per "senior researcher", capital investment per staff member, technicians per scientist, floor space per employee [40:34].

While these measures meet the criteria of a useful measurement, they are insufficient as they do not indicate

the value of work performed, the quantity of work performed, or measure the effectiveness of a research organization.

> For the research administrator the achievements of the research organization are to be found not in repetitious activities, but in activities which create things that are new and of scientific value [40:37].

Some organizations (40:38) use the ratio of sales of new research-developed products to sales of traditional products to measure the effectiveness of research. But this ratio does not consider costs as well as achievements, indicating the ratio of profits of new products to traditional products may be appropriate.

> "The really serious objection to the use of sales figures in determining the effectiveness of research is that they tell us too little about the actual research group--how well it functioned, how much better it could have done judging from other research groups. Sales figures are influenced by too many factors which are unrelated to the efforts and achievements of the research group [40:38].

Another method, reportedly used in the USSR (40:39-40), is based upon the percentage of achievement of research objectives. In this method, a laboratory submits a list of research objectives to a reviewing body for approval and finding. The approved list is compared with actual research objectives accomplished at the end of the fiscal year, and the "percentage fulfillment" is determined. The method is improved when the number of objectives accomplished per unit cost (money, time, manpower, etc.) is considered, and when a weighting is placed on the individual objectives in an attempt to create an appropriate value

for each objective since each objective cannot be of equal value.

> The obvious flow in measurements of publications produced as indicators of research effectiveness is the implicit assumption that all research publications are of equal value, an assumption which is quite false, as all those who are acquainted with scientific research are well aware. . . . Nevertheless, some confidence may be placed in measurements of this type when there are large numbers of measurements involved and their interpretation is statistical [40:42].

(Lipetz uses the terms efficiency and effectiveness synomynously.) Research shows that "statistically, there is a strong correlation between a high rate of publication and a scientist's receipt of high academic honors (40:42)."

> The production of publications is a type of research achievement, and is a practice common to most research organizations. In many research organizations, publications constitute the only tangible achievements. . . . The making of such measurement would not, in most research organizations, be appreciably costly or disruptive. Because this type of measurement is so attractive, it is appropriate to investigate it further to see whether some way can be found to weight or modify the units counted so that the measurements produced will be consistent with the relative values of the publications to which they pertain [40:42-43].

Lipetz suggested that the following guidelines should be used to measure R&D productivity (40:93):

1. Quantifiable objectives must be established.
2. Follow the scientific method.
    a) familiarity with existing knowledge;
    b) hypothesis created, based on knowledge and relationships in a);
    c) prediction of new knowledge deduced;
    d) test validity of the prediction;
    e) new knowledge results from testing;
    f) cycle to a).

Additionally, Lipetz identifies six types of desirable and measurable output of scientific research activity:

1. Description;
2. Definition;
3. Hypothesis;
4. Explanation;
5. Prediction;
6. Experimental technique.

> Each of these elements seems to be identified in quantitative units under certain circumstances. . . . These measurements would make possible the computation and exchange of figures on the efficiency of scientific achievement in scientific research organizations [40:94].

Lipetz (40:94) states that each of the above six outputs can be subdivided to include nearly every other element of identifiable and measurable scientific output.

Lipetz continues with:

> . . . the reason for trying to develop new measurements of research production is to make it easier for administrators to profit from each other's experience by facilitating the interchange of information which correlates administrative methods employed with efficiences obtained. Quantitative information is desirable because it carries a more definite meaning than qualitative information. However, the reliability of the information which an administrator receives, whether quantitative or qualitative, must be determined to his satisfaction so that he may use the information wisely. . . . If the information in question is a subjective evaluation, there is no way to verify its reliability except to make a subjective evaluation of the evaluator. If the information in question is an objective evaluation, based upon something accessible and enduring, its reliability may be confirmed with much greater precision and without reference to the original evaluator [40:109].

The R&D evaluation and measurement process may consist of objective (quantifiable), subjective (nonquantifiable), or a combination of both categories of productivity

measurement criteria. Roman (56:390) stated the following:

> Evaluation involves measurement and should be related to pertinent objectives and standards. Determining objectives is possible in research and development, but establishing standards is extremely difficult, as we have seen, because the work is usually nonrepetitive and lacks precedent.
>
> Evaluation and measurement of R&D effort should start with an appraisal of the individual. It may subsequently survey group performance, which can be greater or less than the sum of the contributions of individual members. The organization's achievement must also be evaluated as a composite of individual and group efforts. Product evaluation, which is more tangible, provides a separate yardstick against which to check the more intangible assessment of human activity [56:390].

Roman further pursued the thought that the individual in the R&D organization should be the starting point for R&D evaluation and measurement as follows:

> The productive unit in R&D organizations revolves around the individual. Although he is only part of the total evaluation and measurement problem, it is necessary to understand the individual's performance in order to attempt a more comprehensive input-output appraisal of R&D effort.
>
> Creative performance is highly unpredictable and impossible to quantify validly with existing methods. Individuals doing creative work have different abilities, and there are no universally accepted standards of efficiency in identifying and solving problems [56:390-91].

In 1968, Roman outlined the following as reasons for needing R&D performance measurements:

> 1. R&D expenditures are increasing;
> 2. Scarcity of R&D specialists;
> 3. Comparatively high salaries of R&D specialists;
> 4. Rising operating costs;
> 5. Competitive pressure for technological progress and stable price levels;
> 6. A considerable portion of R&D expenditure continues to be concentrated on the defense effort;

7. Rising weapons system costs forcing project tradeoffs;

8. A need to measure individual mental performance [56:392-93].

Roman further believed appraisal methods should include both job-related activity and personality factors in "proper balance", yet distinguish between the two.

> Some of the more applicable factors to consider in an appraisal are technical competence, potential technical growth, managerial promise, productivity, quality of work, promotion potential, creativity, ability to work with people, personal habits and appearance, and cost consciousness [56:393].

Roman stated that there is a lack of quantifiable factors in the several individual appraisal techniques used in R&D organizations as of 1968. These techniques are as follows:

1. The forced comparison technique (yields relative position);
2. The totem pole (correlates relative position with salary);
3. The check sheet (evaluates individual characterizations);
4. The McGreggor method (subordinate cites his/her own goals, and self evaluates his/her progress);
5. The publications standard (number of articles published in technical journals) [56:393-395].

Roman provided a short discussion describing the faults with each technique and the possible problems of rater bias, rater consistency, validity of appraisals, and personality conflicts.

> Over the long run, for lack of more acceptable standards, profitability is used as the most concrete measure of an organization's performance. . . . In government, military, and nonprofit units, profit is not a consideration, and the vagueness of the standards used to evaluate the organization makes assessments of individual effort relatively indeterminate [56:396].

In 1968, Roman (56:397-703) proposed identifying project components and establishing a work management system to relate individual assignments to project objectives. The system basically consists of periodically charting the progress, budget, time and money expenditures on a standardized project support assignment form, and for each individual and project on a work standardized form. This form indicates the individual's responsibilities, time schedule, and progress. The Weekly Backlog method is a simpler alternative measuring instrument which records:

1. current work in progress;
2. new work initiated;
3. work completed.

The evaluation of a group, which may represent a function, project, or technical subdivision, may be determined as the collective assessment of the individual's performance; 1) how well the project's objectives are accomplished, 2) the schedule, number of projects accepted, in process, and completed, and 3) expenditures versus achievements (56:404-405).

Roman contended that the two best standards for measuring organizational performance are relative growth and profitability, but these standards cannot be applied to government, military, and nonprofit organizations. Therefore, new methods need to be developed to measure organizational performance. The concepts of effectiveness (ability to achieve its objectives) and efficiency (degree to which

objectives actually achieved) are introduced and defined as possible measures of organizational performance. The order of flow thus becomes 1) established organizational objectives, 2) organizational operation, 3) analyze organizational effectiveness, and 4) analyze organizational efficiency.

"A long range program will give management some indication of how total R&D is contributing to overall organizational objectives (55:408)." Roman suggested that an organization interrogate itself with the following questions to help determine R&D contributions:

1. Is long-range R&D planning related to overall organizational goals?
    a. Is the plan formalized and maintained on a continuing basis?
    b. Does the long range plan identify basic research, applied research, and development within the existing organization structure and in relation to the existing functional activities?
    d. Do the policy-making managers in the research group understand the long-range plan and its connection with corporate objectives?
2. Are projects consistent with the long range R&D plan, and are they being reviewed and updated on a continuous basis?
3. How much of the organization's earnings are derived from products which have been developed by research in the last 5, 10, or 15 years?
4. How many of the products and product improvements were introduced by the organization rather than by competitors?
5. What is the relationship between the use and quality standards of the products being turned out?
6. How many new products are based on in-house research in contrast with licensing arrangements and patent purchases?
7. What is the share of the market?
8. How do patents granted compare with those granted to competitors in number and scope?
9. Has research been a factor in cost reduction programs or increases in productivity?

10. How do research expenditures compare with those of competitors?

11. How do individual competitors score on some of the above pragmatic tests?

12. What is the range of the advanced product planning program and how good is it?

13. Does the research division have good relations with the external groups which it services?

14. Are there recognized innovation and creativity within the research organizations?

15. Are the key people in the R&D organizations strongly motivated?

16. Are there effective techniques within the research organization to encourage value and productivity?

17. Are there enough people and is there a sufficient variety of skills in the research organization behind the key people? Is there a personnel development program?

18. How much confidence is there in the individual who leads the research activity? [55:409].

A natural product can be measured and subjected to comparison, and its approximate value in the commercial market can be assessed. . . . However, . . . the contribution cannot be ascertained conclusively because of inputs from other activities.

Product evaluation is more subjective if there is no market to act as a value barometer. A good illustration is a weapon purchased by the military. Cost and performance can be measured, but the benefit from the product can only be estimated, because its value as a force for deterrence is difficult to calculate. . . .

. . . For lack of a basis for direct comparison, the value of noncommercial hardware and knowledge must be measured in terms of mission requirements and accomplishments [55:411-412].

Roman also discussed input and output determinations, but only on the national level.

Roman listed the following quantifiable and qualitative factors because "they do serve to give a general indication of evaluation and measurement criteria which can be

developed to determine the efficiency of an R&D operation (55:418)."

Quantifiable factors:

1. Costs;
2. The percent of activity (sales) in new projects or products;
3. The number of new products or projects initiated within a given time period as a percent of total product or project mix;
4. Profit;
5. Personnel turnover;
6. The company's or organization's market position;
7. The rate of growth;
8. Patents granted;
9. Research reports.

Qualitiative factors:

1. The prestige and image of the organization;
    a. Professional;
    b. Public;
2. The technical caliber and reputation of the organization's work;
3. The internal morale in the organization;
4. The ultimate benefit to be derived from knowledge in related work;
5. The retention of personnel;
6. The ability, based on technical reputation, to attract capable new people to the organization;
7. The nature of work in process or contemplated as a means of maintaining technical competence and minimizing professional obsolescence [55:418].

> It has been a much more difficult, if not impossible, matter to construct realistic, meaningful indexes or measurements for those organizations or parts thereof (both government and private industry) that are primarily interested in research and development, advice and consultation, health and safety, services of a highly sophisticated and esoteric nature, etc., the end products of which are difficult to determine, let alone quantify [49:656].

Newborn (49:656-657) discussed three measures dealing with the input of labor. The first measure,

quantification of functions, consists of specifying unit objectives, identifying quantifiable objectives, and identifying common quantifications among several organizations for comparison purposes. The second measure, work sampling, is proposed again for group comparisons. Performance appraisal, the third measure, consists of comprehensive judgments made of each unit's performance over a specified time period. Quantitative terms are used to express qualitative judgments.

Szilagyi and Wallace (66:457-458) further expand on the selection of an appraisal method as follows:

> Specifically, the problem for managers is to select a performance appraisal method that is appropriate given the following considerations:
>
> Specific organizational and environmental properties, such as technology, the design of the organization, the firm's industry, and other factors. . . .
>
> Unique individual characteristics influencing performance, including specific skills and abilities and motivation levels.
>
> The mix of specific work behaviors that are appropriate given organizational and individual considerations.
>
> The mix of relevant performance dimensions, given a consideration of the organization and individuals involved.
>
> The specific set of goals to be achieved at departmental and organizational levels.

The above also have application, of course, to non-R&D organizational environments.

The 1973 Collier and Gee report (10:12-17) focused on evaluating both R&D staff performance and the potential

value of completed projects (post-evaluation). This two-step process attempts to answer the following questions:

> 1. How well is the research team accomplishing the agreed upon objectives?
>
> 2. How well is the research organization doing in contributing to the company's commercial objectives? [10:12-13].

A weighted numerical performance rating system is suggested and suppored by examples. A post-evaluation opportunity concept is proposed, where "opportunity is defined as the size of the market for which the product is both technically and economically adequate (10:16)."

Collier (10:16) stated the advantages of this two-step post-evaluation of R&D are as follows:

> 1. Distinguishes between project selection and post-evaluation;
> 2. Applicable to the short term;
> 3. Provides prescriptive feedback;
> 4. Tends to maximize objectivity in R&D evaluation;
> 5. Provides a more common language for research and general management;
> 6. Encourages communication between research and the rest of the organization.

Collier expanded upon his proposed concepts in the 1977 article "Measuring the Performance of R&D Departments" (9:30-34).

> To evaluate the output of R&D operations you must determine how well predetermined objectives have been met and the value of business opportunities generated by completed projects [9:30].

Collier viewed information such as the number of dollars a company made as a result of R&D operations as an improper method to determine the productivity of an R&D

department because this dollar value depends on many factors such as:

1. How well management initially establishes research objectives;
2. How well R&D interprets research objectives;
3. How well the engineering department designs products based on R&D generated technology;
4. How effectively the idea is translated into production;
5. How well marketing and sales personnel perform their specific function; and
6. Log time between initial research and profits.

What is needed, then, is a system that measures the performance of the R&D department as independently as possible from the rest of the company and does so quickly enough for the feedback to be useful [9:30].

Collier presented the argument that generally a company must go through a three step process to create and introduce a new or improved service or product in the marketplace (the responsibility rests with those departments in parenthesis):

1. Determine and agree upon what new technology is needed to achieve the company's goals (R&D, general management, marketing, and manufacturing).
2. Generate the new technology agreed upon (R&D).
3. Apply the new technology to the company's operations in order to achieve the overall goals (Engineering, manufacturing, sales, and R&D).

A critical concept in all of this is that these steps are not simply additive, but utterly interdependent. The productivity of the overall system is not the sum of the individual productivities of each step, but their product [9:30].

Collier (9:31) examined the degree to which the R&D department achieved the agreed-upon objectives and the value of resulting business opportunities in an effort to quantitatively rate the R&D department on an annual basis.

Collier first suggested a participative management approach in setting objectives and employing a weighted average method for accumulating individual project rating scores to determine a departmental performance score. This score compares the actual costs and degree to which technology objectives were achieved against previously established expected costs and technology objectives. The objectives should be challenging yet reasonable. Annual departmental comparisons may be made and the ratings can be used to help determine the distribution of bonuses.

The second step consists of annually evaluating the potential value of the completed research projects. A method for calculating the value of business opportunity created by each project reaching the transition stage to development is proposed. This calculated "return-on-research" number is a ratio of the amount of opportunity produced for every research dollar spent - a "return on research" index of producing opportunity efficiency. The index allows annual company, department, and subgroup comparisons to be made. The difficult calculation is in determining business opportunity.

> The numbers that go into a business opportunity calculation, although sometimes hard to obtain, are mostly objective numbers upon which all parts of the company should be able to agree. Furthermore, if you set up rules on how to use the numbers in calculations, and apply them uniformly, project by project and year by year, the results should be useful in making comparisons. . . .
>
> In terms of what profits the company might actually realize from the technology, obviously the business opportunity numbers are unrealistically

high. For example, the price of the new development would have to be set below the value-in-use price, to give the potential customer a driving reason to switch to your product. It is also unrealistic to expect you could ever reach 100% market share. So these numbers have to be recognized as absolute, "laboratory", values, which would lack credibility for use in discussions with other parts of the company--especially if used to help convince general or marketing management of the value of research, or to persuade them to prosecute a particular project farther [9:32].

Collier provided an example to follow and four recommended rules for using this method, to summarize with:

> There is still much work to be done before I am fully satisfied with the evaluation technique, but I believe it is becoming an increasingly valuable tool in the research director's management armamentarium [9:34].

Seitz (59:26-83) discussed the following five characteristics of productive companies:

1. Effective use of available capital;
2. A well-managed research and development effort;
3. Constructive utilization of human resources;
4. An organization structure that stimulates productivity gains;
5. Adherence to a well-constructed and well-communicated management philosophy or ethic [59:26].

Seitz (59:26-28) stated that recent research indicates that companies may increase their return on R&D by:

1. Improving project selection and management;

2. Encouraging managers to accept projects with higher risk and payout;

3. Strengthening the ties between marketing and R&D departments.

Faust (22:39-42) focused on the concept that today, more than ever, scientists must communicate with senior

management and favorably influence their understanding of and their financial support of R&D. The following subtopics in pharmaceutical R&D are discussed:

1. Assessing the impact of legislation on the cost of research;
2. Determining the cost of drug development;
3. Measuring the productivity of research;
4. Identifying and communicating research needs/strategies;
5. Conveying incentives to invest in research [22:38-42].

In measuring the productivity of research in the pharmeceutical community, Faust (22:40-41) suggested several possibilities:

1. New single chemical entities (NCEs) introduced per research investments;
2. The contribution of NCE's to sales and profits;
3. The importance of NCEs;
4. "Defensive" research investments to comply with changing regulatory requirements;
5. The contribution to the storehouse of pharmeceutical and biomedical knowledge.

Mali (41:100-102) suggested that "Evaluations using checklist indicators can, in an indirect way, measure productivity by specifying the actions to be taken that can measure both performance effectiveness and resource efficiency (41:100)." Several examples are given, including one for an R&D employee which lists 20 indicators as follows:

1. Looks for improvement;
2. Has record of accomplishments;
3. Learns a new assignment quickly;
4. Has a strong will to work, keep busy;
5. Has good work habits;
6. Has a strong sense of commitment to completing work;
7. Is cooperative in teamwork;
8. Is open to ideas and listens well;
9. Uses time effectively;
10. Takes initiative to do things;

11. Is cost minded;
12. Has a strong sense of urgency;
13. Gets satisfaction from a job well done;
14. Contributes beyond what is expected;
15. Knows the job well;
16. Sees things to be done and takes action;
17. Is considered valuable by supervisor;
18. Interacts effectively with other people;
19. Understands organizations and their objectives;
20. Believes in a fair day's pay [41:101-102].

The employee productivity index then equals the ratio of indicators observed with the employee/total number of indicators. This is one method of assigning a quantitative value to qualitative criteria, and may be expanded to projects and groups.

Griliches (27:92-116) outlined a production function approach to estimate the returns to R&D on a national level and relates it to economic growth. The measurement of output in R&D intensive industries and the definition and measurement of the stock of R&D capital are also discussed.

The production function describes the relationship between the final output and the various inputs. The definition and measurement of the stock of R&D capital leads to a discussion and modeling of R&D spillover effects. Industrial sectors and not specific company models are addressed. A significant reference list is provided to further pursue this viewpoint.

Hamelink and Hamelink (28:88-89) provided a model for a performance appraisal which Roman (55:391) previously

pointed out is the starting point for R&D evaluation measurement.

> Consider assigning a numerical value to each key element reflecting its relative importance to the job purpose. Assign also a number to the performance standard and one to the actual performance based on the relative difficulty of accomplishing the particular key element and percentage of accomplishment of that key element [28:88].

If actual performance (AP) less the performance standard (PS) is positive, then the performance is above standard (AS). If AP-PS is zero, then the performance is standard (S). If AP-PS is negative, then the performance is below standard (BS) or deficient (D). Hamelink and Hamelink further develop the analysis to yield vector values and a Root Mean Square (RMS) value in an effort to reduce the subjectivity of performance appraisals and meet the criteria of fairness and accurate employee representation.

In 1980, Karger and Murdick (34:415-430) addressed the measurement of engineering and research (E&R). They state that a measurement and evaluation system must be based on the following principles:

> Measurement and evaluation should be:
>
> 1. Related to company goals;
> 2. Based on long-and short-range technical plans;
> 3. Taken into account when relating the personal goals of the individual professional to the organizational goals discussed in earlier chapters;
> 4. Partially based on standards related to the industry, the nation in which the organization is located, and on similar performance standards in other nations;
> 5. Readily understandable by everyone;

6. Limited to key points and events, like objectives and project milestones;
7. Objective and quantitative, if possible;
8. Able to detect variances and trouble spots quickly;
9. Economical;
10. Provide a stimulus to action [34:416].

To summarize the basic Karger and Murdick approaches to measuring E&R, criteria in the form of objectives or standards must be established and compared with actual performance. The following factors are measurable for this purpose:

1. Inputs:
   a. Money;
   b. Personnel;
   c. Facilities;
   d. Time for major company program or growth;
2. Process (professional performance, managerial and/or technical) against internally generated standards some of which can and should reflect industry standards, represented by goals and objectives;
3. Output as a contribution to the business;
4. Value-in-*exchange* (this is the in-house versus purchase comparison) [34:418].

The quality of E&R may be indirectly determined from an indexing of patents, publications, and citations of work or publications and "some qualitative measurement should always be used (34:419)." E&R may be measured at each management level for internal control (activity direction at the corresponding levels and top management coordination.) Some indexes of <u>input quality</u> are given as follows:

1. Ratio of clerical support to engineers and scientists;
2. Square feet of lab and office space per engineer/scientist;
3. Performance cost per engineer/scientist;
4. Average age of research equipment and instruments;
5. E&R expenditures/sales per year;
6. E&R expenditures/profits per year;

7. E&R expenditures/sales versus national E&R expenditures/GNP;
8. Dollar backlog of projects;
9. Man-years backlog of projects;
10. Average salary per engineer/scientist;
11. Average salary per manager in E&R [34:420].

Current comparison data for industry and the national average may be obtained from the Chamber of Commerce of the United States, Washington, D.C.

Individual output and efficiency equations were discussed and enhanced by time-difficulty and quality of work versus rate of work curves. Some criteria related to determining how much a group contributes to achieving E&R objectives are as follows:

1. Actual development time for a project compared with a projected time based on standards established for the class of product involved;
2. Percentage of dollar change (plus or minus) in average yearly development cost per project by class;
3. Number of new and/or products improved per year (or month);
4. Number of new products completed per year (or month);
5. Change (plus or minus) in the average yearly pay-off per project for a class of products;
6. Change (plus or minus) in total pay-off or profit earned on products designed by the group;
7. Square feet of new design drawings per month for a section;
8. Estimated or actual total pay-off for all products the section has developed;
9. Actual total pay-off for all products developed and put in use on the market;
10. Development cost per person;
11. Development project cost per engineer or scientist;
12. The trend of the ratio of the cost of the E&R unit's cost to the sales volume of its product line, providing this is applicable [34:424].

Most of the group measurements and the following measurement criteria can be applied to the total E&R organization:

> 1. How well is E&R doing in relation to competitors regarding the improvement of products and the finding of new ideas?
> 2. Are the products reliable, easily produced, and maintainable?
> 3. Do the products fit the market needs as interpreted by Marketing?
> 4. Does the E&R organization always have a backlog of potentially profitable projects which it has proposed?
> 5. Is the E&R organization building a reservoir of knowledge and attracting talented new people?
> 6. Are good technical reports of progress issued periodically?
> 7. Are costs of E&R controlled reasonably well?
> 8. Is there a steady flow of patents being issued?
> 9. Is the company forced to pay royalties because E&R failed to invent and patent needed inventions.
> 10. Is the research group "lucky" enough to come up with a very valuable discovery from time to time?
> 11. Have the products been so well designed that customer complaints are at a bare minimum?
> 12. Has the product design protected the company from liability suits? [34:426-427].

Karger and Murdick included a chapter bibliography and summarize the measurement of E&R by stating many qualitative and quantitative criteria may be used to evaluate E&R and the E&R managers should be receptive to applicable evaluation criteria.

> The fact that the tools may be poor does not negate management's responsibility (including the manager of E&R) to measure engineering and research as best it can [34:429].

The proposed theoretical methodologies, indicators, and needs for R&D productivity measurements have been

chronologically presented. The next section identifies the empirical studies which have been conducted since 1960 to reveal the consistencies, contradictions, and novelties between the theoretical and empirical literature.

Empirical Review

> Since technological change is a chief cause of productivity advance, measures of innovational activity in the various industries should be significantly correlated with relative productivity changes. But even if we could catalogue all the innovations made by the firms of each industry in successive periods, further difficulty would be met in trying to weight each in accordance with its relative importance. At best, only indirect measures of innovational activity such as the number of patents issued, are possible [36:182].

Statements similar to the Kendrick quote above are representative of the thoughts concerning R&D activities in the late 1950s and 1960s. Quinn (55:15-42) discussed and provided examples for each of the following three approaches to measuring the productivity of research (current as of 1959); the quantitative, qualitative, and integrated approaches. Quinn interviewed 58 executives from 28 companies to identify yardsticks of industrial research based on this categorization (55:209-219).

The quantitative approach attempts to evaluate the research program and its contributions with the aid of a mathematical formula using one or more of the following factors:

1. Profits from research-created new products;
2. Profits from cost-reducing new or improved processes, methods, or raw materials based upon research;
3. Profits from improved products;

4. Savings from royalty payments avoided;
5. Income from royalty payments received;
6. Miscellaneous profit contributions resulting from general goodwill created by the research establishment;
7. The investment in the R&D program on the total investment to bring research technology to commercial fruition [55:16].

Nearly every company Quinn contacted reported that some form of the quantitative evaluation approach had been experimented with. Both favorable and unfavorable results were reported. Of the companies contacted, 14.8% relied heavily on quantitative devices, 48.2% used some quantitative devices but depend primarily on individual or group judgment, and 37.0% relied little or not at all on quantitative evaluation devices (55:22).

The qualitative approach consists of "broad composite management judgments" made by committees or individual executives. Comments supporting the qualitative approach reflect the following thoughts (55:22-23):

1. Quantitatively, research contributions cannot be differentiated from the contributions of other functional groups;
2. R&D pays for itself. We don't need figures to tell us that;
3. Attempts to quantify R&D are not fruitful at this time;
4. There is no method of evaluation that does not ultimately rely on the judgment of a few individuals.

In the qualitative approach, personal appraisals are pyramided to top management with each higher management level relying on the qualitative evaluation of the next succeeding lower level. The top technical executive then explains and

interprets the technical progress to the top level non-technical president, operating committee, or board. A great deal of faith is placed in the top technical executive.

The integrated approach is an evaluation of how well research integrates with the operating groups of the company using both qualitative and quantitative techniques. In other words, how well does the research activity support broader company operating objectives, since research is an integral part of the whole industrial company.

> The research group should be held responsible for providing required technology for the company just as sales is held responsible for supplying it with customers. The objectives of research, therefore, can only be established in terms of the needs of the particular company which is supporting the research organization. Once these objections are recognized, they define the responsibilities of the research organization and form the basis for measuring its effectiveness [55:31].

The integrated approach attempts to determine whether a research organization is producing results consistent with company objectives at the right times and in the right quantities with the following types of interrogative yardsticks:

> 1. Does the research organization know just what its company needs?
> 2. Is the research organization creating the needed technology?
> 3. Is the research organization helping to get research results applied?
> 4. Are the research organization's operations efficient?
> 5. Is the research management an effective part of the executive team? [55:32].

Several interviews stated that the integrated approach was a primary criterion for evaluating research management, but no one company relied solely on the integrated approach.

In summarizing, Quinn states:

> There can be no single quantitative measure which adequately appraises all important facets of the research effort because there is not even a package of quantitative devices which can be usefully applied to all phases of the research program. Current long-range research results, research efficiency, research quality, and intangible research results defy quantitative appraisal. In the appraisal of certain phases of research, therefore, there is no alternative to the well-reasoned and experienced judgments of individuals or groups. . . .
>
> On the other hand, quantitative techniques offer a degree of objectivity, which cannot be obtained qualitatively. Consequently, quantitative measures are recommended where they are not simply pedantic and where they do not measure with reasonable accuracy what they intend to measure.
>
> Throughout the research evaluation process, the necessity for proper integration with the company's operation must be accepted and judgments concerning the adequacy of integration facilitated [55:41-42].

Quinn uses the term technical evaluation to signify the evaluation of the efficiency and quality of research performance.

> Technical evaluation involves making judgments concerning the period's technical accomplishment without regard to the ultimate commercial consequences of the technology created. . . .
>
> Technical evaluation appraises (1) the efficiency with which researchers achieved the period's planned technological goals, (2) the degree of creativity their work demonstrated, and (3) the technical proficiency, or skill, which their work evidenced. . . .

Efficiency evaluation relates to the actual cost of performing research to some standard which says how much it should have cost [55:62-63].

Volume, efficiency, price, and organizational variances are discussed in relation to efficiency evaluations (55:74-78), and efficiency evaluations are closely interrelated with quality evaluations of research. According to Quinn, creativity and technical proficiency are the two factors which determine the quality of research results. But "standards for judging creativity and technical proficiency are extremely obscure and notably subjective (55:79)." The research executives polled indicated that rankings are used to accurately indicate personnel creativity and technical proficiency in an effort to thoroughly appraise research output. Quality valuations are pyramided to top management in the same manner described under the qualitative approach.

"Commercial success . . . is not a useful criterion for evaluating the quality of research results (55:82)." This statement is supported by examples where the end result of a specific research was the extension of knowledge or the demonstration that an approach to a problem will never be feasible, yet the quality of the research may be very high.

Quinn further stated that factors affecting the use of patents as criteria for quality evaluations include:

1. Time lags between invention and patent issue dates;

2. Actual patent value may be determined years later in a commercial application;
3. Patent value is not indicated by the number of patents per time period;
4. Company patent policy (trade secrets);
5. Subjective judgments are required [55:83-85].

Similarly, the interviews indicated that the use of publications as standards for quality evaluation has several factors to be considered such as:

1. Company publications policy;
2. National (and company) security;
3. Varying quality of the publications;
4. More appropriately used to evaluate an individual [55:86-87].

Few considered the publication rate to be an accurate or usable creativity measure. "No operating or functional manager contacted reported any use of publications as a check on the quality of research results (55:87)."

In 1961, Taylor et al (68:1-3) intensely interviewed 215 physical scientists working in 15 different laboratories at two Air Force basic research centers in an effort to determine methods to predict productivity and creativity. The term contribution is used to mean productive and creative acts. This three year project consisted of:

1. a large interview activity;

2. a study to deal with the contributions of scientists (ID criteria);

3. developing measures of psychological characteristics and validate these measures against the criteria in 2.

Each two year interview pursued the following issues:

(a) types of scientists, (b) kinds of work done, (c) personal background information, (d) probable criteria of scientific productivity and creativity,

(e) suggested ways for recording and scoring behavior on such criteria, (f) nature of the talent in ones own laboratory, (g) ways of predicting success in science, (h) conditions which influence scientific contributions, and (i) other questions which seemed appropriate in each interview situation [68:2].

Resulting interview responses ". . . implied that working conditions have important effects on the quantity and quality of scientists' contributions . . . (68:3)" and included ". . . statements related to the primary goals of the project (68:3)."

An analysis of the interview statements suggested the following kinds of criteria:

1. Ratings by others of the scientist and his scientific products. Typical of such criteria were subjective ratings of productivity by one's supervisors, peers, and a research psychologist; a complex quality and quantity evaluation of publications and research reports; and the collection of quality and quantity information about patents and invention disclosures.

2. Collection of objective facts about each scientist from Air Force records. The number of publications one had produced during a given two-year period with the organization; the number of patents, invention disclosures, and evaluations of them; number of contracts monitored; and organizational background history of each scientist were the major kinds of probable criterion information available from these records [68:3].

Taylor required the following 15 categories to adequately categorize the 52 contribution scores of 166 physical scientists:

A. Productivity in written scientific work;
B. Recent quantity of research reports;
C. Quality (without originality) of research reports;
D. Originality of written work;
E. Scientific and professional society memberships;

F. Actual quantity of work output, as judged by peers, supervisors, and laboratory chiefs;
G. Creativity rating by laboratory chief;
H. Overall performance;
I. Likeableness as an effective member of the research group;
J. Visibility of the scientist;
K. Recognition for organizational contribution;
L. Status-seeking, "organizational-man" tendencies;
M. Current organizational status;
N. Contract monitoring;
O. Total years of work experience [68:10,31].

The validation study was completed on 107 of the above scientists, using 103 predictor scores and 17 criterion scores. . .

For every criterion there were several predictors with low to moderate validity. If an independent sample of scientists were available, effectiveness of best combinations of predictors could be tested. The most predictable criteria, in terms of number of valid scores were likeableness as a member of the research team, professional society membership, current organizational status, judged work output, supervisory ratings on overall performance, and peer rankings on overall productivity.

The psychological scores that were valid for the largest number of these criteria were those for creativity, inner directedness, discrimination of value, professional self confidence, cognition, desire for principles, drive, self-sufficiency, flexibility, independence, intuition, aspiration in quantity of research reports, aspirations in theoretical contributions, aspiration in high level of original work, and intellectual thoroughness [68:31-32].

Mullins (46:52-57) used a questionnaire, a vocabulary test, and nine tests of the Guilford Creativity Battery to survey 131 scientists in an effort to predict creativity. Word association, unusual uses, common situations and plot titles were found to be significantly related to the supervisors' rating criterion. Unusual uses, common situations,

plot titles, consequences, and brick uses were found to be significantly related to publications, the second creativity criterion. None of the predictor variables correlated significantly with both criteria and the two criteria were found to not be significantly related to each other.

The results of Villers (71:65-74) interview with 269 individuals in 34 companies indicated a strong utilization of PERT and GANTT charts for relating technical progress to expenditures. Since most research is programmatic (scheduled; conducted by using a written plan), ". . . the actual expenditures can be clearly related to the expected technical accomplishments (71:77)."

According to Villers (71:77-79), the following four steps were used by many companies which allow researchers to evaluate their technical progress:

1. Periodic review of technical progress;
2. Relate the progress to the schedule;
3. Evaluate the impact of any delay;
4. Select the optimum alternative after the impact of the delay has been determined;
5. Time and money variance analysis.

Villers measured research input by money allocated and research output by technical accomplishment (71:6). The following four points were emphasized as necessary for successful R&D planning and control:

1. Tangible cost vs. potential benefit;
2. Potential language benefits vs. actual short-range expenditures;
3. Encouraging research people to understand the need for profit-making;
4. Encouraging management to recognize the complexity of R&D operations [71:8-9].

Villers (71:108) found that top management needs quantitative measurements of the benefits of R&D activities to decide whether or not specific R&D projects should be pursued. The costs are readily determinable, but the benefits or contributions are not. "The efficiency of research activities cannot be measured by standards such as the rate of production per man-hour or the sales volume during a certain period (71:108)." The following four classes of objections to quantitatively measure the benefits of R&D activities provide support for qualitatively evaluating R&D activities:

1. Rivalry between the various corporate functions (i.e., production and marketing);
2. Rivalry within the R&D personnel;
3. Risk of ignoring some factors (competition);
4. Psychological problems (pressure to perform) [71:109-110].

Villers noted that, in some companies, qualitative reports (standardized forms excluding cost allocation) are submitted to top management to summarize technical accomplishments and their benefits; to state the current status of specific projects; to supply figures that are related in some way to the efficiency of R&D activities. Some of the factors that were considered are as follows:

1. Number of patents (or company's number of patents vs. competitor's number of patents);
2. Number of disclosures presented to the patent attorney by the research people;
3. List of scientific papers presented outside;
4. Royalties received from other companies;
5. Dollars of sales of new products: the trend of the new-product sales measured as a percentage of the total sales for the year;
6. Increase of the company's share of the market for specific product lines;

7. Cost-saving accomplishments;
8. Detailed review of specific areas where technological accomplishments have proved to be especially beneficial to the company;
9. Evaluation of the rank of the company on the market [71:112].

Seiler (58:189-198) surveyed 116 companies in 1965 and reports that there were four major methods used in industry to evaluate research:

1. Ratios;
2. Cash flows;
3. Project cost appraisals;
4. Research income statements;

Seiler concisely reviews each method, articulating several examples, deficiencies, and benefits.

> "Evaluation is a part of planning and should be undertaken in the light of both corporate and research objections. Any effective evaluation system must provide a means of measuring effectiveness and efficiency, but in the case of R&D only broad guages covering fairly long time spans are meaningful [58:197-198].

Eidusun (19:57-63) performed a follow-up study in 1964 of 39 research scientists to compare the rates of productivity with the results of a 1958 study. "The number of scientific publications provided the index of productivity, and was obtained from a detailed curriculum vita submitted by each subject (19:58)." The results show that in general, research scientists:

> maintain a stable productivity rate or even increase their previous performance level. This pattern holds for each age group up to the age of 60. Only when scientists leave research for administration or teaching, or leave the university for industry, do decreases in productivity become apparent [19:63].

Productivity remained constant over time when publications were used as the index.

Burgess (7:85) first categorized Rome Air Development Center (RADC) in-house R&D into the creative, non-creative, and contract support classifications indicated in Table 3-2.

TABLE 3-2

RADC R&D SPECTRUM OF DIRECT ENGINEERING ACTIVITY

IN-HOUSE (CREATIVE)

1. Original ideas with bench-work experimentation.
2. Original study with publication as end item.
3. Suggested ideas with bench-work experimentation.
4. Experiments with unique equipment to derive new techniques or general knowledge.
5. Engineering activity to adapt state-of-art techniques to hardware.

IN-HOUSE (NON-CREATIVE

6. Technical activity in support of scientific committees, symposia, ad hoc groups.
7. State-of-art experiments.
8. Investigations utilizing government facilities against operational equipments.
9. Formulation of technical programs.
10. Analyses and consultations required for operational developments (not identifiable with any contract).
11. Test design and evaluation of equipment.
12. Design development prior to contracting.

CONTRACT SUPPORT (BASIC RESEARCH THROUGH SYSTEMS DEVELOPMENT)

13. Evaluation of unsolicited proposals.
14. Preparation of work statements.
15. Engineering support to procurement during negotiations.
16. Contract monitoring.
17. Acceptance tests exclusive of 11, above.

Burgess emphasized that different types of R&D laboratories (government, industry, and university) perform different work requiring different yardsticks for evaluation (site specific).

> Industry's laboratory program can be evaluated in terms of dollars--new products that create new business and profits for the corporation. How many times have we heard a company brag that 50 percent--or 60 percent--or 75 percent of its products were introduced during the previous three to five years! The university laboratory program can be evaluated in terms of new M.S.'s and Ph.D.'s, or new knowledge. However, the DOD laboratory must measure its effectiveness against its contributions to the technological war in which our country was engaged.
>
> This leads to the first important factor for evaluation: A laboratory, any laboratory, must be evaluated against the long-range objectives and goals of its parent organization [7:86].

The second important factor is stated as:

> The laboratory should stay within its assigned mission, contribute increases in the state-of-the-art, and translate these increases into an increased capability for its corporate organization [7:87].

Furthermore:

> There must be a balance in a research and development program between system requirements and possible long-range application [7:87].

Factors which must be considered in the evaluation of a laboratories' R&D programs are:

1. The corporate objectives;
2. The mission of the laboratory;
3. System requirements vs. possible breakthroughs;
4. In-house vs. contractual efforts;
5. Schedule [7:89].

Burgess further analyzed exploratory development programs over a five year period on the basis of final reports

submitted upon program completion. "To be more valuable, papers presented at symposia, or published in journals, and patents should be included (7:89)." Publications and presentations should not be overemphasized because large numbers of papers and presentations per researcher may detract from determining laboratory effectiveness. The publications were categorized in terms of applicability to determine how well the results contribute to the store of technical knowledge.

> Note that the Government laboratory cannot use the tools available to industry, such as new product lines creating profit, or increased sales, or both. The Government laboratory program culminates in new products; however, the value of these new products must be assessed in terms of increased Air Force capability rather than in dollars and cents [7:89].

Burgess evaluated programs in progress in relation to the following questions regarding the schedules:

> 1) How much will it cost to complete the project?
>
> 2) How much time will it take to complete the project?
>
> 3) How many milestones are left to be accomplished? [7:90].

Lebanoff (39:110-122) analyzed the reporting system used at the Air Proving Ground Center (APGC) from scientific and engineering personnel to top management. The in-progress reporting system should allow management to control the cost, time, and quality of research projects. Project engineers made bi-weekly reports which were analyzed using the techniques of frequency tabulations, percentage calculations, weighted ratios, repression line analysis, correlations,

test of significance, confidence limits, and importance ranking. The resultant data can be reduced with computers to allow management to identify the critical paths within projects. The system was considered to be adaptable to the monitoring of R&D contracts and other problem areas such as the cost, time consumed, and facilities usage in test projects.

Mansfield interviewed 35 companies to explore industrial R&D expenditures. He discussed the major topics:

> 1. What determines the level of a firm's privately financed research and development expenditures?
>
> 2. What is the relationship between a firm's research and development expenditures and various crude measures of inventive output?
>
> 3. Do the largest firms in various industries spend more on research and development relative to their size, than firms one-fifth or one-tenth of their size [43:21-22]?

Mansfield prefaced this exploration by commenting that research and development has an uncertain outcome. Mansfield states the following:

> For example, a recent survey of 120 large companies doing a substantial amount of research and development indicates that in half of these firms at least 60 percent of the research and development projects never resulted in a commercially used product or process. . . . Moreover, even when a project resulted in a product that was used commercially, the profitability of its use was likely to be quite unpredictable [43:16].

In other words, risk and payoff are not easily determined prior to a company's decision to undertake a specific project.

The implication is that an improvement in the methodology used in determining risk and payoff will result in improved R&D productivity.

Mansfield uses data from several industrial companies and mathematical models in his discussion of the three major topics. He stated:

> 1. There is some evidence that the level of a firm's research and development expenditures can be reasonably explained well by a simple model . . . .
> 2. This model may be of use in forecasting research and development expenditures and in estimating the effects on research and development expenditures of changes in relevant policies.
> 3. If . . . one assumes that a firm's desired research and development expenditures, as a percent of sales, are a quadratic function of time, the resulting version of the model seems quite useful for short-term forecasting.
> 4. Except for the chemical industry, there is no evidence that the largest firms in these industries spent more on research and development, relative to sales, than did somewhat smaller firms. In the petroleum, drug, and glass industries, the largest firms spent significantly less; in the steel industry they spent less but the difference was not statistically significant.
> 5. Where the size of the firm is held constant, the number of significant inventions carried out by a firm seems to be highly correlated with the level of its research and development expenditures. In the chemical industry, increases in research and development expenditures apparently result in more than proportional increases in inventive output, but in petroleum and steel there is no evidence of either economies or diseconomies of scale within the relevant range. In most industries, the productivity of a research and development program of given scale seems to be lower in the largest firms than in somewhat smaller firms [43:84-85].

Farris studied the relationship between organizational factors and the performance of 151 electronics engineers "to determine the extent to which the factors

preceded performance and performance preceded the factors (20:9)," and to investigate the "stability of relationships and time lags in measurement (21:87)."

> Four factors were related significantly to subsequent performance; involvement in work, colleague contact, diversity of work activities, and number of subordinates. Every factor studied (these four, plus salary and influence on work goals) was related to previous performance. The performance-factor sequence was much more predominant than the factor-performance sequence. An engineer's performance apparently has pervasive consequences for his social-psychological working environment [20:0].

The results of the Farris self-report-questionnaire from respondents in 1959 and 1965 found that relationships between six organizational factors (involvement in work, influence on work goals, colleague contact, diversity of work activities, salary, and number of subordinates) and four performance measures (contribution, usefulness, patents, and reports) were stable.

Harrold (29:16-23) reported in 1969 that "it is possible to predict laboratory performance with greater confidence than to predict the number of papers and invention disclosures." Fifteen Army laboratories were surveyed to define and evaluate measurable performance indicators. In summary, Harrold (29:22-23) found:

> 1) Generally speaking, knowledge of measurable characteristics can help executives increase their efficiency in the management of a military laboratory complex.
>
> 2) The composition of laboratory personnel is important to Army laboratory output and performance. Age and R&D experience of civilian and military personnel do affect laboratory output and performance.

3) The study indicates that an increase in R&D experience for military personnel of a laboratory would add significantly to its performance and output. However, there are other considerations, such as the military policy of rotation, that can limit the R&D experience of military personnel. An increase in experience must be accomplished in light of policy and other unmeasurables of the military laboratory.

4) While this study emphasized those characteristics that were measurable, other unmeasurables such as employee motivation, morale, and working environment also affect laboratory output and performance. Administrative policies that improve such unmeasurables should continue.

5) Statistically, there was little relationship between the standards of laboratory output and performance. Yet, in each case large increases in obligations ($1 million) only slightly improved output or performance of a single Army laboratory.

6) While it was possible to establish meaningful input/output and input/performance relationships future study over a period of years could consider "lead-lag" elements. That is, measurable characteristics of fiscal years 1965 and 1966 might affect output and performance in subsequent years.

Hill (32:10-19) reported observational and interview data from a field study of a government scientific division (25 scientists) to determine the effect of organizational change on the relationship of leadership behavior patterns to productivity and group morale. Morale was indicated by turnover rate and productivity was measured by publication rate. Only those publications in discipline-relevant journals were counted thus eliminating minor publications and technical reports from consideration. Productivity in the autocratic leadership group was significantly less than in the group with democratic leadership.

In a 1970 study of 70 scientists from three Air Force laboratories at Wright-Patterson AFB OH, Stahl examined

organization facets "that would foster the creativity of the scientists or engineers . . . (61:5)."

A questionnaire methodology testing nine hypotheses was used to:

> . . . measure the degree to which scientists and engineers perceive the organizational factors to be present in their laboratories rather than to objectively measure the degree to which such factors actually exist [61:6].

Stahl found:

> . . . that little differences exist in the perceived presence of the organizational factors among the scientists and engineers who have been working in the laboratories for different numbers of years, and among scientists and engineers when classified as military or civilian. Significant differences exist in the perceived presence of certain organizational factors among the scientists and engineers in different laboratories, in different educational levels, engaged in different kinds of work, in different grades and among scientists versus engineers [61:113].

and these differences are based on:

> . . . twenty-four organizational factors that affect the creativity of scientists and engineers in Air Force R&D laboratories. These twenty-four factors are:
>
> 1. Management receptivity to new ideas;
> 2. An incentive system that researches creativity;
> 3. Time for independent research;
> 4. Open communication channels both vertically and horizontally in the organization;
> 5. Freedom in scheduling work hours;
> 6. Freedom in choice of problem;
> 7. Freedom and autonomy in work procedures and methods;
> 8. Recognition for creative accomplishments;
> 9. Challenging work;
> 10. Stimulating colleagues;
> 11. Organizational acceptance of conflict and dissent;
> 12. Organizational acceptance of nonconformity;
> 13. Employee understanding of organization objectives;

14. Little administrative distractions and routine duties;
15. Excellent facilities;
16. Little fear of failure;
17. Sufficient time to just think;
18. Organization structure flexibility;
19. Opportunity for professional society participation;
20. Opportunity to publish;
21. Relaxed, flexible controls;
22. Management encouragement of and confidence in employees;
23. Participative management;
24. Dual promotion ladders [61:113-114].

Further breakdown on the differences are presented in Stahl's conclusion (61:113-120).

Whitley and Frost (75:161-178) states:

> Of particular importance for developing adequate indexes of individual and collective performance is the specification of goals. Both an understanding of what goals the individuals and the institution as a whole are expected to achieve and what goals are, in fact, seen as a salient by the members of the organization are fundamental to develop useful measures of performance [75:162].

The pros and cons of basic and applied performance measures for individuals and organizations in Table 3-3 are discussed (75:104).

TABLE 3-3

CLASSIFICATION OF PERFORMANCE MEASURES

OBJECTIVE	SUBJECTIVE
Number of papers	Prestige ranking by peers
Number of books	Prestige ranking by members of other groups
Number of citations	Supervisor evaluation
Number of professional awards	Colleque evaluation
Number of powerful positions held	Executive evaluation
Individual members output	Members evaluation of organization relative to 'top 10'
Library facilities	University evaluation
Number of graduate students	Professional society evaluation
Number of outside visitors	
Cost and schedule overruns	
Number of adopted innovations	
'Parellel projects'	

> Inter-organizational comparison of the performance of individual scientists is not possible, we suggest, unless the objectives of the research are similar in the organizations concerned [75:173].
>
> The measurement of performance in research laboratories, for example, becomes the understanding of how different solutions are produced to technical problems in different environments. To improve the quality of such solutions, we have to know both how they were reached and what they are required for. This involves the detailed and systematic study of how knowledge is created by scientific activity which necessitates in turn investigating what scientists do in identifying and representing problems and selecting and applying research strategies and tactics. It also involves the study of the interrelations between ideas and products and processes both technological and social. The problem of measuring knowledge is created and used in society. Many of the difficulties encountered to date in developing performance measures, we suggest, are due to the failure to recognize this basic implication [75:174-175].

Whitley and Frost fully supported their discussion of the objective and subjective performance measures with an extensive bibliography of references through 1971.

Glass (25:2-12) summarized the techniques used by Doll in evaluating the effectivness of its in-house R&D as of 1972.

> In examining Defense R&D laboratories, many different types of appraisals have been used: supervisory evaluation, program evaluation, special appraisal, visiting committees, and the national competition of laboratories for important programs [25:3].

The following six techniques are presented and discussed:

> 1. Organizational climate (actions to improve organizational health);
> 2. Management surveys (management improvement);

3. Organizational model (reorganization);
4. Model for failure (emphasizes mishandling pitfalls);
5. Statistical and economic models (mathematical input-output relationships);
6. Peer rating (personnel and organizational).

Participating management, including the development concept paper (DCP), was experimentally being applied to segments of DoD research and technology programs.

> Instead of trying to relate organizational effectiveness to a generalized model or set of criteria, this concept permits the appraisal of an organization based upon tailored goals that are specific to that particular organization. In the long run, this is considered to be the most useful and meaningful approach to laboratory evaluation. The trick will be to define the goals and objectives in quantitative terms and to develop related tools and performance measures [25:11].

Vincent and Mirakhor (72:45-53) analyzed the questionnaire responses from 94 scientists and engineers in the Missile Systems Laboratory of the U.S. Army Missile Cammand. This empirical investigation revealed that:

1. Job satisfaction is a multidimensional factor;

2. The results generally agree with similar study results;

3. There is a statistically significant relationship between productivity and satisfaction (72:45).

Productivity was objectively measured by:

1. The number of professional journal publications;

2. The number of patents or patent applications;

3. The number of manuscripts or unpublished technical reports (72:46).

> Considering satisfaction, those with high satisfaction publish at a higher rate, at a lower age and taper off less sharply. Those of low satisfaction publish later and taper off sharply.
>
> It should be noted that the most productive group with respect to publication of papers is the group with high job satisfaction in the 10-25 thousand dollar-per-year pay range. These persons were also predominantly in the 26-to-35 year age group. Furthermore, the number of papers published is only an indicator of productivity and does not give consideration to the all-important matter of quality of the paper.
>
> Patent disclosures or inventions are considered to be the most important and meaningful productivity indicator of a scientist or engineer working in a laboratory [72:48].

The highest rate of patent disclosures occurs with the 30-35 age group with high satisfaction who is in the 15-19 thousand dollar pay range (72:48). The presentations indicator of productivity reflects that the 40-45 age group in the 20-25 thousand dollar pay range with 25 years experience give more presentations. The net result is that young low-salaried researchers produce more publications and patents, and middle age researchers tend to give more presentations (transmission of ideas and experience) (72:50).

Andrews and Farris (3:185-200) derived five-year panel data from approximately 100 scientists in a NASA laboratory to determine the effects of time pressure and individual performance. Respondents completed a lengthy questionnaire in both 1965 and in 1970. Individual performance was evaluated by selected laboratory professionals. Innovation, productiveness, and usefulness were the performance criteria utilized to express how well or poorly each

researcher performed relative to other researcher's similar training and experience. They are defined as follows:

> The performance criteria included the following:
> Innovation--the extent the man's work had "increased knowledge in his field through lines of research or development which were useful and new."
> Productiveness--the extent the man's work had "increased knowledge along established lines of research or development or as extensions or refinements of previous lines," and
> Usefulness--the extent the man's work had been "useful or valuable in helping his R&D organization carry out its responsibilities" [3:188].

Andrews and Farris concluded that the highest performing researchers tended to desire relatively large amounts of pressure, and that performance was likely to suffer when pressure differed substantially from the desired pressure.

Edwards and McCarry (18:34-41) reported in a 1973 literature review that considerably more study is needed to accurately evaluate the quality and quantity of the work of a research staff. The definition of scientific output is given as follows:

> 1. The discovery of new facts;
> 2. The invention of new methods of doing things;
> 3. Combining known concepts to create new devices [18:34].

Overall performance methods reviewed are:

> 1. ratings/rankings;
> 2. number of patent disclosures;
> 3. contributions to scientific knowledge;
> 4. contribution to the organization (18:34-35).

The quantity of written output reviewed consists of:

> 1. number of papers published;
> 2. number of citations;
> 3. number of books published;

4. number of patents;
5. number of unpublished reports;
6. number of patent applications;
7. number of papers presented at professional meetings (18:35-36).

The quality of output reviewed consists of:

1. ratings/rankings;
2. significance of research reports;
3. relevance - timeliness of research reports;
4. organization - lucidity of research reports;
5. originality of research reports;
6. elegance - accuracy - exhaustiveness of research reports;
7. complexity of the research assignment;
8. amount of research supervision received;
9. demands of originality and lack of guidelines;
10. scientific qualifications and contributions of the scientist;
11. citation count (Science Citation Index) (18:36-38).

The summary states:

> A review of the studies on measurement of scientific performance reveals very little agreement from one investigator to another as to what constitutes scientific output or what measures should be used to reflect the output. . . . A few in-depth studies of scientific performance have revealed that scientific output is multidimensional and cannot be satisfactorily measured by any one criterion alone. . . .
>
> A factor analytic study which reduces scientific performance to a few practical, workable components would have great utility for the research community [18:40].

McCarry and Edwards (45:43-49) also interviewed 72 research biologists in four Canadian Government laboratories in 1973 to determine the relationship between scientific accomplishment and the characteristics of effective organizational climates. The following nine performance measures were utilized:

1. Rank (by peers) of the incumbent's total bench work "mission-oriented" productivity;

2. Rank (by peers) of the incumbent's creativity of role performance, i.e., originality, stimulation, and uniqueness of mission-related problem solving;

3. Departmental percentile standing;

4. Extradepartmental recognition score, i.e., invited addresses, journal reader or editorship, etc.;

5. Rank (by peers) of the incumbent's communications performance, i.e., clarity and organization in receiving, comprehending and transmitting range of oral and written contents (it was necessary to partial out effects of friendship stucture on communications rank);

6. Quality;

7. Originality ratings of refereed journal publications by discipline peers;

8. Citation rate, viz., number of citations received per paper over a five year time interval;

9. Publication rate, weighted for differential authorship, viz., number of papers per year with a correction for author position [45:441-442].

O'Brien assumed effectiveness is a function of the quantity and quality of the output of the General Systems Engineering/Technical Director (GSE/TD) process and that effectiveness is measured in terms of documented information (51:7). The paper reports a study of 812 scientists in 23 engineering teams in the organization of the Deputy for Engineering, Aeronautical Systems Division in 1973. This one-month study documented all their output quantitatively and qualitatively. All written and verbal information being transmitted outside the GSE/TD team was recorded and assessed as team output. Output quality was quantified with weightings in a "sum approach" and a "product approach." Output quantity was determined from the number of pages of documents and verbal communications memoranda

in the 2037 output assessment forms completed and processed.

Harrison (30:234-241) reported the results of an empirical study of 95 scientists in three large research laboratories to relate perceived role performance to the system of management. The four perceived performance measures were as follows:

1. Esteem of fellow scientists;
2. Contribution to knowledge in the field;
3. Contribution to management objectives;
4. Sense of personal achievement.

Harrison concluded with the following statements:

> . . . the hypothesis that the more organic the system of management the higher the perceived role performance of the individual scientist was accepted.
>
> The evidence suggests that perceived and, presumably, actual role performance in a research laboratory will be improved if the scientist is encouraged and permitted to participate actively and regularly in the setting of objectives and making of decisions [30.241].

Katzen (35:24-28) graphically presented the performance profiles of 11 scientists in the form of ratings versus a seven year time frame.

> . . . engineers are involved in a wide variety of activities, ranging from fundamental research through applied research and development to design, operation, plant and technical services, sales, etc. The output for each type of function is different, which again is difficult to relate by quantitative measurement. In certain activities such as research, development, and design, the quality of the output is even more important than the quantity, and the innovative or inventive value is a major factor which does not lend itself to quantitative measurement [35:24].

Katzen's technique for performance measurement consists of an effectiveness measure and an efficiency measure expressed in percentages. Effectiveness was measured as a percentage of working hours the engineer has put in on specific projects over the total hours monthly available (excluding unassigned time, vacation time, sick leave, and meetings). Efficiency was determined by assessing whether or not all the effective work hours were fully productive. The ratings in Table 3-4 were applied to 11 scientists (35:26).

TABLE 3-4

EFFECTIVENESS AND EFFICIENCY RATINGS

EFFECTIVENESS	EFFICIENCY
90% - highly effective	95% - excellent
85% - very satisfactory	90% - very good
80% - good, but subject o improvement	85% - good
	80% - fair
75% - fair to poor, inexperienced	75% - poor, inexperienced

Ferguson (23:33-35) reported the implementation of an MBO program at Erling Riis Laboratory to develop and carry out research projects. Key Work Objections (KWO) define priorities and establish activities and are a main input for annual performance appraisals.

> Being involved in setting goals, the researcher is more apt to be working in his true areas of interest. . . . Productivity is more easily measured by the key work objectives system and performance appraisals are more objective. In general, we have found that the use of KWO's stimulate teamwork, orient effort, and establish definite, objective goals that lead to increased productivity [23:34].

Whelan (74:14) reported in 1976 that Union Carbide employs a one sheet questionnaire form to descriptively categorize projects and measure R&D effectiveness. The R&D categorization questionnaire informs corporate management of the following:

> 1. Documentable estimates of the relative amounts of corporate R&D effort being devoted to maintenace of existing business versus the quest for new business;
>
> 2. Relative effort on high-risk versus low-risk objectives;
>
> 3. Other parameters of the total R&D program.
>
> With the availability of data for several successive years obtained on a consistent basis, it is possible to see trends in R&D posture reflecting the R&D response to dynamic corporate goals as well as the impact of budget variations on R&D objectives [74:14].

Koser surveyed 135 scientists/engineers in an Air Force laboratory in a 1976 thesis study of the relationships between selected organizational and individual variables and an objective, quantifiable measure of scientist/engineer productivity. The study includes ". . . the selection of variables that, in previous studies, have been shown to be correlated to some definition of scientific and engineering performance (38:3)." Koser utilized a set of variables

similar to the set investigated by Stahl for the purpose of comparison. Koser briefly reviews the publications of Stahl, Vincent and Mirakhor, Pelz and Andrews, Mullins, Meltzer and Salter, Eidusun, Hill, Farris, Andrews and Farris, Pelz, and Martino. The final list of output consisted of:

1. technical reports;
2. work unit planning documents;
3. journal articles;
4. procurement packages;
5. evaluation of proposals;
6. computer codes;
7. technical presentations;
8. management presentations [38:18].

Stahl and Koser (63:20-24) used these same eight output variables in a 1978 publication.

Stevens (66:9-10) used the terms innovation, original, useful, and productivity (as defined by Stahl (62:91-92)) to investigate rewards in Air Force R&D. Stevens used the following quantifiable output variables:

1. New or improved products;
2. New or improved process techniques;
3. Patents/patent applications;
4. Published papers in technical or professional journals;
5. Air Force technical reports;
6. Air Force technical memorandums;
7. Books;
8. Manuscripts;
9. Hardware/software specifications;
10. Test plans;
11. Test reports;
12. Statements of work;
13. Requests for proposal;
14. Oral presentations to technical/professional audiences [66:35].

The survey involved 278 scientists/engineers in one Air Force laboratory to determine relationships between

productivity and rewards for output. A discussion of results is provided in Stevens' thesis (66:101-108).

Stahl (62:33-74) summarized empirical studies between 1951 and 1974 relating:

> . . . specific organizational variables with a measure of output of scientists and engineers in an R&D setting, or with a measure of original output in a controlled laboratory experimental setting [62:33].

The 1976 Stahl study (62:93-188) analyzed 41 organizational predictor variables and the two criterion variables productivity and innovation defined as follows:

> 1. Productivity: Quantity of scientific output.
>
> 2. Innovation: Quality of scientific output, original and useful [62:91].

Three Air Force laboratories (154 civilian and military scientists/engineers) were surveyed. The peer ratings for innovation and productivity within the same work group were found to be reliable criterion measures. Productivity (quantity) reliability was found to be consistently just higher than the innovation (quality) reliability. "This is somewhat expected since productivity might have been an easier construct to grasp than innovation (62:122)."

Stahl also found:

> A significant positive relationship between the productivity ratings and number of Air Force Technical Reports and Technical Memorandums.
>
> A strong positive relationship between the innovation and productivity scores. This observed relationship agrees with three other

studies cited in the literature that also found strong positive relationships between the two criteria [62:180].

For the given definitions, productivity and innovation measures were shown to be reliable and valid and have utility in measuring the productivity and innovation of scientists/engineers in R&D (62:81). The most significant findings are as follows (62:181-184):

1. Rewards for innovation are positively related to innovation, and to productivity, and to the joint criteria at both the individual and group levels, and is the variable most consistently related to performance.

2. Communication with other professionals within the group on technical matters is consistently related to performance. It is positively related to innovation, productivity, and the criteria at the group level.

3. The group leader's empathy and participation on goal setting are both positively related to productivity and to the joint criteria at both the individual and group level, but neither variable is related to innovation.

4. The age-education variables: The age x education interaction variable, age, length of scientific/engineering experience, length of federal government employment as a scientific/engineering experience, length of federal government employment as a scientist/engineer and education variables are all consistently related to performance at the individual level. All are negatively related to innovation, and to productivity, and to the joint criteria. The age x education interaction variable has the strongest negative association with innovation.

5. Autonomy is not found to be related to either innovation or productivity.

6. Communication with the group leader on technical matters is curiously negatively related to innovation in both the individual and group level regression analysis.

Stahl and Steger published two similar papers in 1977 (64:71-76; 65:35-38) in the open literature revealing

much the same information as previously given by Stahl (62:180-184). But the studies also revealed:

> . . . that those individuals classified as highly productive had an average 3.2 publications for every year of professional work, the innovative group had an average of 2.5 publications per year, and those classified as non-innovative and nonproductive had an average publication count of .18 per year of professional activity [64:37].
>
> Communication with other professionals within the group on technical matters was consistently related to performance. It was positively related to innovation, productivity and the bivariate criteria at the individual level, as well as to innovation at the group level. . . .
>
> Participation on goal setting and the group leader's empathy were positively related to productivity and to the joint criteria at both the individual and group level. Neither variable is related to innovation [64:74-75].

Bakalkin and Pitak (5:1-3) reported that over a five-year period in the Ukranian Scientific Research Institute of Refractories,

> . . . 184 projects were undertaken, from them 133 were introduced into industry and 49 were passed on for use in planning and design.
> The actual cost benefit per ruble of expenditures grew from 1.57 rubles in 1971 to 3 rubles in 1975. . . . The output per worker (scientific research and junior technical personnel) during this period increased from 4,500 rubles to 5,080 rubles [5.2].

Thus, technology transitions (to industrialization) and cost benefits per ruble expenditure were two Soviet applied science performance measures in 1977.

Corbin (12:1-35) explored the relationships of individual and supervisory variables to the productivity (quantity of output) and job satisfaction (Hoppock) of

326 surveyed scientists and engineers in the Air Force Flight Dynamics Laboratory (AFFDL). Only quantitative output measures similar to those used at AFFDL by Stevens (66:35) were used. A complete statistical analysis revealed the following:

> No relationship was found between productivity and job satisfaction. Although higher education, grade, and experience were associated with higher productivity, no single predictor variable was shown to be significantly associated with all six of the productivity variables. . . [12:124].

Coile tested the square root theory of scientific publication productivity: the postulate model stating that "half of all scientific papers in a field are contributed by a few highly productive authors numbering approximately the square root of the total of scientific authors (8:1)." The scientific productivity of chemists listed in Chemical Abstracts whose names began with the letter A or B were selected - a total of 6,891.

> The 84 most productive chemists, the square root of 6,891, contributed 4,207 papers of the total 22,839 papers, or 18 percent--considerably less than the 50 percent asserted by the model [8:1].

Porter (54:28-30) described the following five benefits Mobil Research has experienced since 1960 from estimating the value of the results of completed R&D:

> 1. Motivate researchers;
> 2. Help identify high business risk objectives;
> 3. Demonstrate research productivity;
> 4. Identify productive research areas;
> 5. Increase confidence in predictive evaluations.

In support of item #3, demonstrate research productivity, Porter states the following:

> The post audits show that, on the average, the value of our research exceeds its cost several times. And they have shown corporate management that the quantifiable value of research fluctuates widely from year to year, because most of the value is derived from a few very large accomplishments, and in some years no large ones mature (54:29).

In 1978, Stahl and Koser (63:20-24) used the eight output variables identified by Koser (38:18) and found:

> The net result of using the weighting methodology was a set of highly reliable weights which implies that it was a viable methodology. However, its very high correlation with unweighted output implies that it is essentially the same measure. Due to the restriction of range arising from the two year time limitation on output, it is suggested that such a weighting scheme be used only for longer time periods of output [63:24].

A 1978 technical report by Stahl (a follow-on analysis of Koser's 1976 thesis) (60:1-15) again used the eight output variables identified by Koser (38:18) to investigate the measurement and prediction of productivity in the Air Force Weapons Laboratory. Supervisors and scientists/engineers ranked the outputs similarly except for technical reports.

> The producers, on the average, are more educated, communicate with other scientists and engineers within their own section more frequently, attend more professional society meetings, are concentrated in greater numbers in one office, and have a stronger perception of being rewarded for productivity than their nonproductive counterparts [60.13].

The Hughes Aircraft Company published the results of Phase I and Phase II studies of R&D productivity improvement in 1978 covering the following main topics:

1. Productivity improvement considerations;
2. Improving operational productivity;
3. Improving managerial productivity;
4. Improving employee productivity;
5. Productivity profiles [33:183].

The bibliography (33:107-175) is divided into the same categories and represents the largest published single source reference for R&D productivity publications encountered by the investigator.

> The initial study phase (1973-74) involved (1) participation of 27 organizations in industry (primarily aerospace), government, and education, (2) a survey of 350 R&D managers regarding currently used techniques for evaluating and improving productivity, (3) the services of 13 prominent consultants, (4) attendance at eight productivity seminars, and (5) an extensive literature search. . . .
>
> A second study phase (1975-77) involved (1) participation of an additional 32 organizations in industry (primarily consumer product), government, and education, (2) a survey of 2000 R&D managers and senior technical personnel to identify counter productive factors and effective techniques for dealing with these factors, (3) the services of an additional 15 prominent consultants, (4) attendance at 15 productivity seminars, and (5) a continuation of the literature search. . . .
>
> Study findings clearly indicate that skilled, responsible management and superior productivity are inseparable. . . .
>
> The study findings also show that the specific approach to improving productivity is unique to each individual and organization; there is no universal formula. However, there are certain basic principles which encompass productivity improvement and generally apply to all organizations [33:vi-vii].

The key factors to productivity are given as effectiveness, efficiency, and value. The section titled evaluating R&D productivity (33:39-47) was of primary interest. The Hughes' study participants generally agreed that:

1. Management should periodically evaluate R&D productivity.
2. Line managers best evaluate their own organizations.
3. Frequent informal assessment is desirable.
4. Group output can typically be evaluated in terms of:
    a. actual design performance versus requirements;
    b. actual cost/schedule versus planned cost/schedule;
    c. overall customer satisfaction.
5. Evaluation must be tailored to each application.
6. Useful evaluation techniques include:
    a. work sampling;
    b. productivity ratios and trends;
    c. patterns of performance.
7. Any attempt to evaluate productivity should consider employee response to that evaluation.
8. The evaluation of group output is psychologically more acceptable than individual evaluation [33:39-47].

Decotiis and Dyer (15:17-22) interviewed twenty industry R&D scientists and engineers to identify the following five dimensions of project performance:

1. Manufacturability and business performance;
2. Technical performance;
3. Efficiency;
4. Personal growth experience;
5. Technological innovativeness.

The interview also empirically identified the following 12 determinants of project performance:

1. Management support;
2. Inter-organizational relations;
3. Sponsor relations;
4. Transfer management;
5. Planning and stability of specifications and designs;

6. Project leader-functional manager relations;
7. Clarity of project leader role;
8. Project members' skills and cooperation;
9. Communication, decision-making, and personnel utilization;
10. Planning and scheduling;
11. Control procedures;
12. Leadership [15:18].

DeCotiis and Dyer suggested a model to predict project performance based on the 12 determinants above.

Dekok (16:75) and Rutley (57:48) used the same list of equally weighted productivity categories in their assessments of team development at the Air Force Flight Dynamics Laboratory (AFFDL). The list consists of the following:

1. Published papers in professional or technical journals;
2. Technical reports;
3. Technical memorandums or test data reports;
4. Presentations at symposia, meetings of professional organizations, and technical conferences;
5. Hardware/software specifications, statements of work, requests for proposals;
6. In-house studies, technical and/or managerial assessments;
7. Presentations to general officer-level audiences;
8. Professional or technical committee participation (external to laboratory).

The National Research Council (NRC) (48:50-87) reviewed the official government measures of productivity (concepts, methods, and sources).

> Following a brief overview of government measures, the rest of this chapter is divided into sections on each of the major classifications of the economy for which official productivity measures are prepared: economy-wide, industry divisions, selected detailed industries, and the federal government [48:50].

Output indexes for detailed industries and selected federal government activities are given (48:66-78) and referenced here as typical non R&D measures of productivity. Some of these indexes are as follows:

1. Unweighted quantity index;
2. Unit-value weighted quantity index;
3. Unit-employee-hour weighted quantity index.

NRC also reported the shortcomings and limitations of output and input measures.

Day (13:61-66; 14:55-60) interviewed top executives in a two-part article directed toward solving the mystery of productivity measurement. Day quoted Rockwell vice president of operations Edward Loesur as stating:

> "Many engineering and office managers abhor the thought of measuring their outputs. . . . Yet engineering managers will readily talk about performance improvements in terms of weight removed, reliability attained, or new performance features of products they have designed." [13.65].

Universal productivity measures may never be developed, but:

> Edward J. Freney Associates, a Redding, Connecticut, human resources consulting firm, claims that performance standards can be established for any job--even creative ones. The key factor is using the workers to help establish them. Once they're agreed upon, employees will measure their own output and quality, and prompt and consistent feedback encourages improvement [13:66].

<u>Discussion</u>

The literature review consists of 13 theoretical publications and 41 empirical publications chronologically

arranged and presented from 1959 to 1980. What does this computation tell us? Is there agreement between the theoretical and empirical literature or do the two sets of publications represent conflicting data and views? Does the empirical data support or deny the theoretical lines of thought? This section examines the consistencies, contradictions, and novelties (as identified in the literature review) concerning the following productivity measurement categories:

1. Objective criteria;
2. Subjective criteria;
3. Both objective and subjective criteria;
4. Situation specific.

Consistencies. Tables 3-5 and 3-6 reveal the percentage of theoretical and empirical publications which use productivity measurement indicators which are subjective only, objective only, or both subjective and objective. The theoretical literature (Table 3-5) is applicable to both industry and government and therefore results in a single row of "combined government and industry" data. The empirical literature (Table 3-6) "combined government and industry" row is a summation of the singularly identified government and industry data. Four empirical publications are not included in Table 3-6 because they were literature reviews. Empirical percentages for government and industry using both subjective and objective productivity indicators are very similar (58% and 62% respectively) and are collectively higher than the theoretical value for "combined government and industry"

TABLE 3-5

THEORETICAL LITERATURE STATISTICS

	SUBJECTIVE ONLY	OBJECTIVE ONLY	BOTH	TOTAL
Combined government and industry	23% 3	31% 4	46% 6	13

TABLE 3-6

EMPIRICAL LITERATURE STATISTICS

	SUBJECTIVE ONLY	OBJECTIVE ONLY	BOTH	TOTAL
Government	8% 2	33% 8	58% 14	24
Industry	23% 3	15% 2	62% 8	13
Combined government and industry	14% 5	27% 10	59% 22	37

(46%). The empirical, objective only government value of 33% more than doubles that of industry (15%). Both the government and the combined government and industry percentages (33% and 27% respectively) roughly equal the theoretical, objective only value of 31%. The empirical, subjective only government value is only 8% whereas the empirical subjective only industry value is 23% (equal to the theoretical, subjective only combined value). In summary, these comparisons indicate that (for the literature review):

1. Both government and industry utilize a combination of subjective and objective productivity

indicators (59%) more than the theory suggests should be done (roughly 22% more).

2. Government laboratories rely on objective only indicators to the same degree that the theoretical literature suggests they should, whereas industry laboratories appear not to be influenced by the theoretical findings.

3. Industry laboratories rely on subjective only indicators to the same degree that theoretical publications suggest they should, whereas, government laboratories do not follow the suggestions of the theoretical literature.

TABLE 3-7

CONSISTENTLY INDENTIFIED R&D PRODUCTIVITY INDICATORS (OBJECTIVE AND SUBJECTIVE)

Budget (costs, cost ratios, cash flow)
Checklist
Competitive comparisons (rankings, ratings)
Customer satisfaction
Effectiveness (objectives accomplished)
Efficiency (input/output ratios, percentages)
Intra group communication
Morale
Number of patents (issued, applied for)
Number of presentations
Number of publications (books, journals, rates, technical unpublished manuscripts)
Originality (ideas, studies, program formulation)
Performance appraisals
Periodic reviews
Procurement packages
Progress charts (PERT, GANTT)
Quantification of qualitative judgments
Reputation
Schedule (milestones)
Trends
Work unit planning document

Consistent theoretically and empirically identified R&D productivity indicators are given in Table 3-7. R&D productivity evaluations must use multiple criteria as

there is no single quantitative measure which can adequately appraise all the facets of a research and development effort. Every productivity indicator is subject to dispute. The criterion for inclusion in Table 3-7 is that the indicator is common to both theoretical and empirical literature, and was mentioned at least four times in the literature reviewed.

Contradictions. Table 3-8 is a listing of the productivity indicators found to be included in either the theoretical or empirical literature and also refuted in either the theoretical or empirical literature. For example, profit, profit ratios, and market share may be good measures for some industry R&D organizations, but do not apply to government R&D laboratories. Preparation of work statements and

TABLE 3-8

CONTRADICTING R&D PRODUCTIVITY INDICATORS IDENTIFIED (OBJECTIVE AND SUBJECTIVE)

Commercial success
Contract monitoring (weighting)
Number of citations
Number of publications (weighting)
Personnel turnover
Preparation of work statements
Profit
Profit ratios
Quality
Share of market

contract monitoring are contradicted because all statements of work and contracts are not of equal value in time

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requirements and in dollar value. Various weighting schemes can be applied to these types of indicators, but the weightings are not common to all laboratories or supported by different managers.

Novelties. There are nearly as many novelty R&D productivity indicators identified in Table 3-9 as there are consistent indicators in Table 3-7. The novelty indicators are categorized as such because of the low frequency (3 or fewer) of occurrence in the publications reviewed. The majority of indicators were mentioned only once in either the theoretical or empirical literature. The relatively large number of indicators are indicative of the concept of laboratory specificity or the failure of other laboratories to publish their use of these indicators.

TABLE 3-9

NOVELTY R&D PRODUCTIVITY INDICATORS IDENTIFIED (OBJECTIVE AND SUBJECTIVE)

Amount of research supervision required
Colleague communication
Hardware software specifications
High risk versus low risk projects
Likeable group members
Manufacturability
Number of graduate students
Number of visitors
Professional society evaluation
Profit contributions resulting from goodwill created by the research establishment
R&D effort ($) to maintain existing business versus R&D effort in quest of new business
Scientific and professional society memberships
Sense of personal achievement
Technology transitions
University evaluation
Usefulness
Variances (schedule, budget, performance)

CHAPTER 4

DATA COLLECTION

Introduction

The third area of interest in this thesis is that of identifying the state-of-the-art of productivity measurement criteria (organizational and individual) as practiced by both DoD and selected private industry laboratories. The author attempted to contact all DoD laboratories as identified in the latest available DoD in-House RDT&E Activities report (69:xxv-xxxi). This reference describes the mission, facilities, and funding for each laboratory in the 14 Air Force, 34 Army, and 22 Navy laboratories and centers. Military and civilian contacts and corresponding phone numbers were obtained from the September 1979 publication Institutional Barriers on DoD Laboratories: A Report of the Ad Hoc Task Group on In-House Laboratories to the Deputy Under Secretary for Research and Advanced Technology (52:14-29). An extensive telephone survey was conducted. Responses were obtained from 14 Air Force (100%), 30 Army (88%), and 20 Navy (91%) laboratories and centers for an overall DoD response rate of just more than 91%. A total of 21 industry laboratories were interviewed as taken from the list of attendees to the 1980 International Conference on Productivity Research sponsored by the Houston-based American Productivity Center (APC). The selections were

made on the basis of "most likely to include an R&D laboratory," resulting in 21 usable responses. The 21 companies clearly are not representative of all industry companies, but are representative of those 44 "most likely to include an R&D laboratory" companies identified in the aforementioned listing.

A telephone interview methodology was chosen for the following reasons:

1. A higher response rate can be anticipated.
2. A telephone interview is inherently more personal than a formal questionnaire.
3. Additional avenues can be explored.
4. Ambiguities are minimized.
5. Responses can be more accurately evaluated.
6. Investigator familiarity with the subject matter (in this case DoD and industry laboratories) can be enhanced.
7. The investigator has a greater degree of control in choosing the level of laboratory management to interview.

Each interview began with a formal introduction stating the investigator's name, school, location, statement of purpose, how the information would be used, and a request for voluntary participation in the thesis effort. The average time per interview was approximately 25 minutes. Three phone calls were required per laboratory, on the average, to determine the proper individual to talk to, and then to reach that individual. The telephone interview is a very time consuming and, thus, demanding data collection methodology--singularly the greatest disadvantage.

The majority of interviews revealed there is a great deal of interest in the subject of R&D laboratory

productivity, a fact the investigator used to his advantage while questioning. Each interview concluded with a restatement of purpose, how the information would be used, a request to be included on the thesis distribution list, and a request for permission to quote (if needed) and to list the company (laboratory) name as a participant in the thesis. Six companies preferred anonymity and are listed as such in Table A-4; e.g., B Company, C Company, etc.

Interview Instrument

The telephone interview questionnaire utilized (Appendix B) was developed to obtain a maximum amount of information for the eight questions solicited. Productivity classification (Q2a) and laboratory productivity indicators (Q3) were the major thrust of the interview. A standardized response form was developed to facilitate note taking and to reduce the interview time per laboratory. Response confidentiality was emphasized and maintained for every laboratory.

Question 1 intended to determine which laboratories had any published productivity studies which were (are being) conducted in the respective laboratories. The studies may have been (be) conducted internally, or by an external organization which may have conducted (conduct) the research through a thesis effort, or by contract, or by higher corporate management.

The productivity classification question, Q2, determined whether subjective or objective indicators were used in each laboratory. The methods used to determine individual productivity add to the overall knowledge of laboratory productivity measurement.

The nature of specific objective and subjective indicators were identified by Q3. This question is the primary thrust of the interview. After the initial 14 interviews were conducted with the Air Force laboratories, a listing of common responses emerged. This listing became a standardized reference asked of all the remaining interviewees. Air Force indicators such as research fellows, training/employee/year, and sick leave usage are not included because these did not emerge until late in the interviewing process and were therefore not asked of all Air Force laboratories. The 18 objective indicators are as follows:

1. Status vs. milestones;
2. Degree technical objectives are accomplished. (i.e., Project A is 77% complete);
3. Number of patents/year;
4. Number of publicatons/year;
5. Ratio of man hours expended/research dollar expended;
6. Ratio of expected sales/investment dollar ratio;
7. Collective determination of individual productivity;
8. Expenditures vs. budget;
9. Periodic reviews;
10. Ratio of overhead/direct costs;
11. Ratio of workload/researcher;
12. Research fellows contribution;
13. Laboratory personnel education and credentials;
14. Training/employee;
15. Sick leave usage;

16. Technology transitions, (i.e. research to exploratory development or military to civilian application);
17. Problems solved or identified;
18. Consultations to organizations external to the laboratory (DoD and Industry).

Each respondent was asked for additional indicators at the end of the listing. This method reduced the time required for each interview and increased the validity and reliability of the interview results by reducing the number of indicators the respondent may not immediately remember during the interview.

The sources of new R&D projects are identified by Question 4. Q4 is designed to determine how laboratory personnel resources are utilized in project selection. The responses are intended to identify the most common sources of specific projects; i.e. upper management direction, lower management recommendation, technical and professional recommendation, or external identification (user and industry). The results are intended to indicate the effective use of personnel resources.

The utility of laboratory productivity measurements are identified by Q5. The thrust of the question concerns what comparisons are made; e.g. the use of productivity measurements to improve individual motivation (through awards and promotions), or the ratio of technical objectives accomplished/dollar expenditure, etc.

The purpose of Q6 is to determine what factors the laboratories consider to be the primary components of

laboratory productivity. Efficiency (output/input ratios) and effectiveness (performance of mission) determinations were specifically asked for and any other terminology which may apply were pursued.

Permission to list the laboratory (company) and permission to quote (as needed) was solicited in Q7. The small number of thesis copies available for distribution and the large number of requests for copies of this thesis prompted the investigator to volunteer to mail the Accession Document (AD) number to each responding laboratory (company) (Q8). An accurate formal address, name, and title for each respondent was compiled for this purpose.

Interview Results

The majority of interview results are presented in Tables 4-1 to 4-8. Both the actual numbers and percentages are given in each block. The percentage values are rounded to the nearest 1%, accounting for any summation variances from 100%. The interview responses do not warrant further statistical analysis as is common with questionnaires soliciting responses on an ordinal scale; e.g. 1-7. The Tables of data and discussions are presented in the same order the interview questions were asked.

Table 4-1 reflects the response rates for each category of laboratories resulting in an overall response ratio of 75%, which is indeed higher than many written questionnaire response rates (38:32; 65:43; 12:23; 16:63; 56:32). The private industry response rate was determined on the

TABLE 4-1

LABORATORY RESPONSE RATIO AND LEVEL OF LABORATORY MANAGEMENT

	TOTAL NO. LABORATORIES	RESPONSE RATIO	LEVEL OF LABORATORY MANAGEMENT UPPER	MIDDLE	LOWER
Air Force	14	100% 14	71% 10	21% 3	7% 1
Army	34	88% 30	90% 27	10% 3	0% 0
Navy	22	91% 20	95% 19	5% 1	0% 0
Government	70	91% 64	88% 56	11% 7	2% 1
Industry	44	48% 21	76% 16	24% 5	0% 0
TOTAL INTERVIEWED	114	75% 85	85% 72	14% 12	1% 1

basis of 21 responses out of 44 companies "most likely to include an R&D laboratory", as enumerated in a listing of participants to the International APC Conference. Removing the industry figures result in just over a 91% response rate for all DoD laboratories, a statistic reflective of laboratory interest. Additional private companies were not pursued due to the time constraints of this research. An attempt to keep all responses from the same level of laboratory management was not possible due to vacations, travel duty, and referrals. Therefore, a record of the respondent's laboratory management level was made and resulted in fairly high upper management response (85%), a low middle management response rate (14%), and only one lower management response (1%). This information is important because the perceptions of laboratory productivity may not be the same at the different management levels in a laboratory.

Table 4-2 shows the response data relative to productivity measurement studies currently underway in addition to the studies which have been conducted either internally or externally since 1970. All government laboratories are collectively considered. The data are not completely accurate due to the wording of the question, i.e., "Are you aware of . . . ." The respondent may not have been aware of all productivity measurement studies since 1970, and there are at least four cases where the respondent voluntarily admitted to less than one year occupancy in his present

TABLE 4-2

PRODUCTIVITY MEASUREMENT STUDIES

	SINCE 1970 (COMPLETED)				CURRENTLY (ON-GOING)		
	INTERNAL	EXTERNAL	PUBLISHED	TOTAL	INTERNAL	EXTERNAL	TOTAL
Industry	9	2	1	11	7	2	9
Government	20	15	13	35	12	9	21

INTERNAL = PERFORMED BY OWN ORGANIZATION

EXTERNAL = PERFORMED BY SEPARATE UNRELATED ORGANIZATION

PUBLISHED = OPEN LITERATURE

management position. Responses relative to current ongoing research is considered accurate.

Table 4-3 clearly reveals that the greater majority of all R&D laboratories incorporate a combination of subjective and objective criteria in determining their productivity. Only four industry laboratories did not determine laboratory productivity due to the complexity of the task. The results further emphasize the point that objective indicators are not easily developed as indicated by the higher percentage of laboratories relying on subjective determinations when both subjective and objective criteria are not used.

Individual researcher productivity was unanimously determined at least in part on the basis of performance appraisals. The various performance appraisal systems are as follows:

1. General Performance Appraisal - Industry;
2. OER - Officer Efficiency Report - DoD;
3. GMAS - General Managers Appraisal System (1 JUN 81) - AF;
4. JPAS - Job Performance Appraisal System (1 OCT 81) - AF;
5. MPS - Merit Pay System - Army and Navy;
6. GPAS - General Performance Appraisal System - Army.

These systems incorporate the concepts of Management by Objectives (MBO) (1:83) and a participative leadership style (1:391-392). Additional individual productivity criteria include, but are not limited to the following:

1. The number of novel ideas generated;
2. The number of patents;
3. Patent submissions, and invention disclosures;

TABLE 4-3

PRODUCTIVITY MEASUREMENT CLASSIFICATION SUMMARY

	OBJECTIVE ONLY	SUBJECTIVE ONLY	BOTH	NEITHER	TOTAL
Industry	0%	19%	62%	19%	100%
	0	4	13	4	21
Government	2%	6%	92%	0%	100%
	1	4	59	0	64
Air Force	0%	14%	86%	0%	100%
	0	2	12	0	14
Army	3%	0%	97%	0%	100%
	1	0	29	0	30
Navy	0%	10%	90%	0%	100%
	0	2	18	0	20

4. The workload and quality of projects;
5. The number of original publications produced both in-house and contributed to the public literature;
6. The number of publications in referee journals;
7. Peer quality reviews;
8. The achievement of target and overtarget objectives;
9. The number and quality of presentations given;
10. The number of conferences attended;
11. Professional society involvement and recognition;
12. The level of effort expended;
13. Project salesmanship and visibility for funding support;
14. Periodic (every three-to-six months) reviews;
15. Performance within the budget;
16. Variances (cost and schedule);
17. Critical path performance;
18. Value added per labor hour;
19. Problems solved.

Table 4-4 shows the results of Q3a (Appendix B), the objective indicators of R&D productivity. Objective indicators most common to industry and government R&D are status vs. milestones, degree technical objectives are reached, expenditures vs. budget and periodic reviews. Predominantly, objective indicators of R&D productivity in the government include the number of publications/year, collective determination of individual productivity, research fellows contributions, laboratory personnel education and credentials, training/employee, sick leave usage, technical transitions (both military to civilian application and, e.g. basic research to advanced research), problems identified and solved, and consultations to organizations external to the laboratory. The only objective

TABLE 4-4 *

INTERVIEW RESPONSES RE: OBJECTIVE INDICATORS OF R&D PRODUCTIVITY (ORGANIZATIONAL)

	STATUS VS. MILESTONES	DEGREE TECHNICAL OBJECTIVES REACHED	# PATENTS/YR.	# PUBLICATIONS/YR.	MAN-HOURS/$ EXPENDITURES	EXPECTED SALES/INVESTMENT $
Industry	52% 11	48% 10	38% 8	29% 6	29% 6	52% 11
Government	86% 55	78% 50	39% 25	73% 47	31% 20	0% 0
Air Force	79% 11	79% 11	7% 1	43% 6	36% 5	0% 0
Army	93% 28	73% 22	63% 19	90% 27	30% 9	0% 0
Navy	80% 16	85% 17	25% 5	70% 14	30% 6	0% 0

*Table 4-4 continued on pp. 97 and 98.

Table 4-4 (Cont'd)

INTERVIEW RESPONSES RE: OBJECTIVE INDICATORS OF R&D PRODUCTIVITY (ORGANIZATIONAL)

	COLLECTIVE INDIVIDUAL PRODUCTIVITY	EXPENDITURES VS. BUDGET	PERIODIC REVIEWS	OVERHEAD COSTS DIRECT	WORKLOAD RESEARCHER	RESEARCH FELLOWS CONTRIBUTION
Industry	29% 6	48% 10	62% 13	24% 5	19% 4	5% 1
Government	72% 46	61% 39	91% 58	38% 24	27% 17	38% 19
Air Force	36% 5	64% 9	79% 11	7% 1	21% 3	NOT ASKED
Army	83% 25	73% 22	100% 30	50% 15	33% 10	33% 10
Navy	80% 16	40% 8	85% 17	40% 8	20% 4	45% 9

TABLE 4-4 (Cont'd)

INTERVIEW RESPONSES RE: OBJECTIVE INDICATORS OF R&D PRODUCTIVITY (ORGANIZATIONAL)

	EDUCATION & CREDENTIALS	TRAINING EMPLOYEE	SICK LEAVE USAGE	TECHNOLOGY TRANSITIONS	PROBLEMS SOLVED/ID'D	CONSULTATIONS TO OUTSIDE ORGANIZATIONS
Industry	14% 3	14% 3	5% 1	38% 8	33% 7	19% 4
Government	55% 35	60% 30	50% 25	69% 44	64% 41	64% 41
Air Force	21% 3	NOT ASKED	NOT ASKED	7% 1	29% 4	21% 3
Army	70% 21	77% 23	67% 20	90% 27	73% 22	87% 26
Navy	55% 11	35% 7	25% 5	80% 16	75% 15	60% 12

indicator of R&D productivity in industry alone is expected sales/investment dollar ratio, which does not apply to government R&D. Less important objective indicators of R&D productivity common to both industry and government R&D are the number of patents/year, the ratio of man-hours expended/research dollar expended, the overhead/direct cost ratio, and the workload/researcher ratio.

Nearly every respondent commented that at least one of the 18 standardized indicators was measured but not for the purpose of measuring laboratory productivity. For example, the ratio of overhead/direct costs may indeed be tracked, but it is not used as an indicator of laboratory productivity because the overhead costs are not within the control of the laboratory. Therefore, it becomes necessary to emphasize to each respondent to indicate whether or not each of the 18 standardized and any additional indicators are used in determining laboratory productivity. As a result, all objective indicator responses are uniform in that they reflect actual measurements taken to determine laboratory productivity but may also be used in other reporting documents.

Additional objective indicators of R&D productivity not included in the table are as follows:

1. Project output/investment cost;
2. Personnel commitment rates;
3. Obligation rates;
4. Disbursement rates;
5. Fieldings (equipment or techniques which are incorporated into operational use);
6. The in/house/out-house ratio;

7. Man-hours expended;
8. The number of presentations given;
9. Workload/research department;
10. New vaccines;
11. Treatments;
12. Diagnostic technical advancements.

These objective productivity indicators were not common enough to tabulate, but are worthy of mention. The last three indicators are clearly usable for a medical R&D laboratory but do not apply to other R&D laboratories. This represents a good example of the inability to develop universal laboratory productivity indicators without making these indicators overly general. The unique inherent missions, personnel, and facilities of each laboratory tend to indicate that a specific set of indicators should be developed to account for the uniqueness of each type of laboratory (medical, electronic, armament, etc.), if not for each laboratory itself. In addition to these objective indicators, several subjective indicators were identified. These subjective indicators are teamwork (the ability of a group to work together), laboratory reputation, and sponsor feedback (feedback from the organization sponsoring the research).

A subjective determination of laboratory productivity was found to occur in all but four (17 of 21) industry laboratories. Table 4-5 reveals that R&D laboratories perceive their productivity to be determined more by upper laboratory management and higher corporate management than by each laboratory management level. Industry responses

TABLE 4-5

SUBJECTIVE LABORATORY PRODUCTIVITY DETERMINATION

	COMMANDER/ DIRECTOR/ DIVISION CHIEF	HIGHER CORPORATE MANAGEMENT	EACH LABORATORY MANAGEMENT LEVEL	NONE
Industry	24% 5	38% 8	33% 7	19% 4
Government	83% 53	69% 44	56% 36	0% 0
Air Force	79% 11	29% 4	43% 6	0% 0
Army	87% 26	77% 23	60% 18	0% 0
Navy	80% 16	85% 17	60% 12	0% 0

indicate that a subjective evaluation of laboratory productivity is roughly equivalent at all three levels, and differs dramatically with the overall government figures. Navy responses place greater perceived subjective laboratory determinations at the higher corporate management level while both Air Force and Army subjective laboratory determinations are perceived to occur more frequently at the commander/director/division chief level. The Air Force response rate of 29% at the higher corporate management level is extremely low when compared to Army (77%) and Navy 85%) responses, but part of this large variation may be attributable to the fact that the Air Force laboratories were the first set of laboratories interviewed and, as such, may reflect some effect from the formulation of the standardized list. The percentages do not sum to 100% because many of the laboratories gave multiple responses, indicating the level of determination, and that determinations are also made at other levels.

Table 4-6 shows the sources of new R&D projects; the specific approaches to be taken to comply with higher corporate guidance (directives). No single management level is dominant. The high industry (86%) and government (100%) values for the technical and professional recommendations category represent a strong reliance on and an effective use of laboratory personnel in project selection. Government figures for special committees (86%), user identification (75%), and consultants (56%) average over 21%

TABLE 4-6

SOURCES OF NEW R&D PROJECTS

	MANAGEMENT				TECHNICAL/ PROFESSIONAL RECOMMENDATIONS	SPECIAL COMMITTEES	USER IDENTIFIED	CONSULTANTS
	UPPER	MIDDLE	LOWER	ALL				
Industry	38% 8	10% 2	5% 1	57% 12	86% 18	67% 14	57% 12	29% 6
Government	19% 12	5% 3	16% 10	64% 41	100% 64	86% 55	75% 48	56% 36

higher than the respective industry figures (67%, 57%, 29%). The industry laboratory value for upper management (38%) doubles the government percentage (19%) indicating that the government methodology for selecting new R&D projects is less centralized than the method used in industry.

Special committees are the second most reported sources of new R&D projects (industry - 67%, government - 86%). Commonly used project selection committee names are as follows:

1. Corporate Board;
2. Corporate Planning Group;
3. Executive Program Council;
4. Internal Quality Control Group;
5. Proposal Review Board;
6. Research Advisory Council (RAC);
7. Research Planning Committee (RPC);
8. Steering Committee;
9. Strategic Planning Group;
10. Technical Advisory Committee (TAC);
11. Technological Base Review Committee,
12. Technology Center Management Committee;
13. Technical Directorate Group;
14. Technical Forecasting Program Committee;
15. Technical Planning Board TPB;
16. Technical Thrust Committee.

The committees typically evaluate on-going programs, proposed new projects, contract proposals, and overall mission objectives. User identification of programs (marketing in industry and operational commands in DoD) is the third most reported source of new R&D projects and consultants (external to the laboratory) are the fourth most reported source of R&D projects. The percentages indicate that there is an effective use of laboratory personnel and external references.

The utility of laboratory productivity measurements are revealed in Table 4-7. A self comparison as a function

TABLE 4-7

UTILITY OF PRODUCTIVITY MEASUREMENTS

	SELF COMPARISON OVER TIME	COMPETITIVE COMPARISONS	TO IMPROVE INDIVIDUAL MOTIVATION	NO COMPARISONS	TECHNICAL OBJECTIVES ACCOMPLISHED ANNUAL COST	ALLOCATION OF RESOURCES
Industry	67% 14	43% 9	29% 6	29% 6	48% 10	20% 4
Government	81% 52	42% 27	69% 44	14% 9	55% 35	50% 32
Air Force	71% 10	29% 4	7% 1	29% 4	57% 8	43% 6
Army	83% 25	47% 14	80% 24	7% 2	50% 15	40% 12
Navy	85% 17	45% 9	95% 19	15% 3	60% 12	60% 12

of time is the main purpose of making productivity measurements. Only 15 respondents indicated there was no comparisons made at all, and six of these laboratories do not use objective indicators. Competitive comparisons are an important use of productivity measurements, but many respondents pointed out that it is a very difficult task to obtain competitive data with which to make such comparisons. The utility of productivity measurements to improve individual motivation, examine the ratio of technical objectives accomplished/annual cost, and the allocation of resources and mission alignment are also important uses.

Self comparisons as a function of time are consistently higher for government laboratories than for industry laboratories. Competitive comparisons are roughly equivalent (in percentage) for all laboratories, with Air Force laboratories lagging slightly behind the average (29% vs. 42%). The government utility of productivity measurements to improve individual motivation nearly triples the industrial utility (69% vs. 29%). Of the government laboratories, Air Force laboratories do not use productivity measurements to improve individual motivation to the extent that Army and Naval laboratories use them (7% vs. 80% and 95%). This difference may be partly explained by the higher percentage of Air Force laboratories found not to make any productivity comparisons at all (Air Force - 29%, Army - 7%, Navy - 15%). The 29%

TABLE 4-8

PRODUCTIVITY COMPONENTS: EFFICIENCY, EFFECTIVENESS, AND OTHER FACTORS

	EFFICIENCY	EFFECTIVENESS	NEITHER	OTHER
Industry	43% 9	52% 11	43% 9	Value Factors Customer Satisfaction Schedule Sales Ratios Employee Cohesiveness
Government	41% 26	75% 48	23% 15	
Air Force	29% 4	50% 7	50% 7	Project Criticality Fieldings Inefficiency
Army	40% 12	77% 23	23% 7	Fieldings Responsiveness Reputation Timeliness Management Utilization
Navy	50% 10	90% 18	5% 1	Responsiveness Customer Feedback Reputation Innovation Missed Opportunity

of industry laboratories making no productivity comparisons just more than doubles the 14% of government laboratories not making productivity comparisons. The utility of productivity measurements to determine the ratio of technical objectives accomplished/annual cost ranges from a low of 48% to a high of 60% for all laboratories, indicating a similar distribution for this category. The utility of productivity measurements to determine the allocation of resources is 150% higher in government laboratories than in industry laboratories (20%), with Navy laboratories leading the rest (60%).

Table 4-8 data reflects that the effectiveness component of productivity is determined more often than efficiency in government R&D and in the private companies interviewed. Because of the nature of R&D, the laboratory responses indicate a higher priority to determine mission accomplishment over efficiency. Army and Navy laboratory percentages for efficiency and effectiveness are significantly higher than those values for Air Force laboratories, and correspondingly, the percentage of Air Force laboratories using neither efficiency nor effectiveness as components of productivity is significantly different than the Army and Navy laboratory values. Other productivity components which are used either instead of or in addition to efficiency and effectiveness are also listed.

Selected Quotations

Several comments concerning various aspects of R&D productivity were made during the telephone interviews which could not be properly tabularized. These comments are included because they often reflect multiple respondent feelings and offer insight to the problem of R&D productivity measurement.

> "Technical reports, journal articles, in-house publications and presentations to scientific conferences are used as a good measure of organizational productivity and quality of product."

> "Subjectively, a partial indication of laboratory productivity is given by the successful implementation into operational use."

> "There is no universal formula to precisely measure R&D productivity. I feel it is better to evaluate productivity based on both quantitative and qualitative factors rather than try to strictly measure productivity with precise quantifications. A situation-specific evaluation method should be established by each sector manager. The purposes of this qualitative and quantitative criteria are 1) to evaluate sector productivity, and 2) to report the results to the next management level. Once the historical base is established, the emphasis should be to monitor and improve productivity."

> "R&D laboratory productivity indicators aid the company in determining whether or not the right people are being hired."

> ". . . defines productivity as the ratio of Output of Valuable Projects to Investment Cost. Productivity Indicators are the ratio of R&D dollars to Revenue dollars, and the project's value to the user organization."

> "Productivity indicators permit the identification of both organizational weaknesses and strengths, and aid in determining how best to allocate dollar, personnel, and faciliate resources."

"Laboratory leadership is most important for motivating people and keeping on top of technology. Salesmanship and visibility are additional factors considered in establishing a project's funding level."

"Progress in development can be more easily measured quantitatively than basic research which is necessarily more subjective."

"Productivity measurements help laboratory management determine the projects which will yield the best product possible for the user, to determine projects with the best ROI."

"Productivity measurements are used in part to determine the efficiencies of our functional managers in accomplishing the annually increasing number of tasks."

". . . it is not appropriate to apply productivity to direct labor in R&D laboratories, and that the emphasis should be on what we are doing and are we making any progress."

"R&D productivity indicators should be used to best determine resource allocation, organizational alignment, and for supervisory performance evaluations."

"R&D laboratory productivity measures help determine which new projects should be investigated, which projects should be terminated, the allocation of resources, and identify the productive and nonproductive individuals in the organization."

". . . the operational commands need a more direct mechanism to communicate their needs to the laboratories for small projects and problems."

"One major component of productivity in our laboratory is the quality of the scientific journals which accept our articles, indicating the quality of our publications."

"Many objective indicators have a high degree of inherent subjectivity and these indicators depend to a large degree on the management style and management goals established in each individual laboratory."

Summary

A telephone interview methodology was chosen to determine the state-of-the-art of productivity management in 21 industry, 14 Air Force, 30 Army, and 20 Navy laboratories, resulting in an overall response rate of 75% and 91% for DoD laboratories. The interview results are tabulated and interpreted for each question. Upper laboratory management provided 85% of all responses.

The majority of laboratories (government - 92%, industry - 62%) use both subjective and objective measures of productivity. Individual productivity measurements are based on a form of performance appraisal. Status vs. milestones, the degree technical objectives are reached, expenditures vs. budget, and periodic reviews were the most common (of 18) indicators to both government and industry laboratories. Additional indicators were identified. The use of technical and professional recommendations, special committees, customers, and external consultants indicates the effective use of laboratory response. Self comparisons and competitive comparisons are the primary purposes of productivity measurements. Effectiveness is a more important component of productivity than efficiency is. Interviewee comments offer insight to the problems of R&D productivity measurement and provide additional information which cannot be easily tabulated.

CHAPTER 5

Summary of Research

This investigation into the state-of-the-art of productivity measurement in the research and development community consisted of exploration into three distinct areas of interest:

1. A review of the theoretical literature of industry and DoD laboratories.

2. A review of the empirical literature of industry and DoD laboratories.

3. An extensive telephone interview of industry and DoD laboratories.

These three interests were pursued using two methodologies: an exhaustive search of the theoretical and empirical literature, and an extensive telephone interview process conducted with 64 DoD and 21 industry laboratories. R&D productivity and its components were defined and consistently used throughout this thesis. The literature review identified the objective and subjective R&D productivity indicators both proposed and utilized from 1960 to the present.

The study limited its focus to the measurement of R&D productivity. Productivity improvement and factors affecting laboratory productivity were not explored. To serve as an initial step for follow-on study, references for these related topics are included in the expanded Related Sources of the Bibliography. Theoretical and empirical literature of

R&D productivity indicator similarities, contradictions. and novelties were identified.

Summary of Results

A chronological listing of 13 theoretical and 41 empirical publications were listed in Appendix C and presented in Chapter 3. Twenty-one consistently identified similar R&D productivity indicators, ten contradictory indicators, and 17 novelty indicators were identified from the literature in Tables 3-7, 3-8, and 3-9. Consistent indicators were those indicators found to be common to both the theoretical and empirical literature and were mentioned at least four times. Contradictory indicators were those indicators found to be included in either the theoretical or empirical literature and also refuted in either the theoretical or empirical literature. Novelty indicators were the indicators found to occur three or fewer times in the publications reviewed.

The telephone interview instrument was used to survey 21 industry, 14 Air Force, 30 Army, and 20 Navy laboratories resulting in an overall response rate of 75% and 91% for DoD laboratories. Upper laboratory management provided 85% of all responses. Individual productivity measurements are based on a form of performance appraisal. Status versus milestones, the degree technical objectives are reached, expenditures versus budget, and periodic reviews were the most common (of 18) indicators to both government and

industry laboratories. The use of technical and professional recommendations, special committees, customers, and external consultants indicates the effective use of laboratory resources. Self comparisons and competitive comparisons are the primary purpose of productivity measurements. Effectiveness is perceived as a more important component of productivity than efficiency is. Interviewee comments offer further insight into the problems of R&D productivity measurement.

The majority of laboratories interviewed (government - 92%, industry - 62%) used both subjective and objective measures of productivity. Combined subjective and objective indicators were suggested by 46% of the theoretical "combined government and industry" category and by 59% of the empirical "combined government and industry" category. The incidence of laboratories utilizing both subjective and objective measures was clearly dominant for the literature and for the surveyed laboratories, but less dominant for the literature. When "subjective only" and "objective only" categories are examined, "objective only" indicators were preferred in the literature, whereas the subjective only" indicators were the preference of the interviewed laboratories. Of the 18 standardized interview indicators, training per employee, problems solved/identified, consultations to outside organizations, and workload per researcher were not identified in the literature. The "research fellows contributions" interview indicator was

found to be a novelty indicator in the literature. All remaining interview indicators were classified as consistent literature indicators.

Recommendations

The following recommendations evolved out of the results of this research and other research on productivity measurement in R&D laboratories.

1. Duplicate the interview to validate the findings of the present study. The literature review should also be updated to reflect the most current theories and the most recent results of empirical investigations.

2. An expanded literature search may be enhanced by taking full advantage of the National Technical Information Service listing, for which a fee is charged.

3. Consider the investigation of R&D productivity improvement rather than the direct measurement of R&D productivity. Methods for productivity improvement and factors affecting R&D productivity are more readily available and may be more beneficial.

APPENDICES

APPENDIX A

DEPARTMENT OF DEFENSE RESEARCH AND DEVELOPMENT LABORATORIES AND PARTICIPATING INDUSTRY LABORATORIES

TABLE A-1

AIR FORCE RESEARCH AND DEVELOPMENT LABORATORIES

AEROPROPULSION LABORATORY
AEROSPACE MEDICAL RESEARCH LABORATORY
ARMAMENT DEVELOPMENT AND TEST CENTER
AVIONICS LABORATORY
ENGINEERING SERVICES CENTER/RD
FLIGHT DYNAMICS LABORATORY
FRANK J. SEILER RESEARCH LABORATORY
GEOPHYSICS LABORATORY
HUMAN RESOURCES LABORATORY
MATERIALS LABORATORY
ROCKET PROPULSION LABORATORY
ROME AIR DEVELOPMENT CENTER
SCHOOL OF AEROSPACE MEDICINE
WEAPONS LABORATORY

TABLE A-2

NAVY RESEARCH AND DEVELOPMENT LABORATORIES

AEROSPACE MEDICAL RESEARCH LABORATORY
AIR DEVELOPMENT CENTER
BIOSCIENCES LABORATORY
CIVIL ENGINEERING LABORATORY
CLOTHING AND TEXTILE RESEARCH FACILITY
COASTAL SYSTEMS CENTER
DAVID W. TAYLOR NAVAL SHIP R&D CENTER
DENTAL RESEARCH INSTITUTE, NTC
ENVIRONMENTAL PREDICTION RESEARCH FACILITY
HEALTH RESEARCH CENTER
MEDICAL RESEARCH INSTITUTE
MEDICAL RESEARCH UNIT NO. 2
MEDICAL RESEARCH UNIT NO. 3
OCEAN R&D ACTIVITY
OCEAN SYSTEMS CENTER
PERSONNEL RESEARCH & DEVELOPMENT CENTER
RESEARCH LABORATORY
SUBMARINE MEDICAL RESEARCH LABORATORY
SURFACE WEAPONS CENTER
UNDERSEAS RANGES DEPARTMENT
UNDERWATER SYSTEMS CENTER
WEAPONS CENTER

TABLE A-3

ARMY RESEARCH AND DEVELOPMENT LABORATORIES

AEROMEDICAL RESEARCH LABORATORY
ATMOSPHERIC SCIENCES LABORATORY
AVIATION R&T LABORATORY
AVIONICS R&D ACTIVITY
BALLISTIC RESEARCH LABORATORY
CHEMICAL SYSTEMS LABORATORY
COLD REGIONS R&E LABORATORY
COMBAT SURVEILLANCE & TARGET ACQUISITION LABS
COMMUNICATIONS ELECTRONICS COMMAND
CONSTRUCTION ENGINEERING RESEARCH LABORATORY
ELECTRONIC WARFARE LABORATORY
ELECTRONICS TECHNOLOGY & DEVICES LABORATORY
ENGINEER TOPOGRAPHIC LABORATORIES
ENGINEERING WATERWAYS EXPERIMENT STATION
FIRE CONTROL & SMALL CALIBER WEAPONS SYSTEMS LAB
HARRY DIAMOND LABORATORIES
HUMAN ENGINEERING LABORATORY
INSTITUTE OF DENTAL RESEARCH
INSTITUTE OF SURGICAL RESEARCH
LARGE CALIBER WEAPONS SYSTEMS LABORATORY
LETTERMAN ARMY INSTITUTE OF RESEARCH
MATERIALS AND MECHANICS RESEARCH CENTER
MEDICAL BIOENGINEERING R&D LABORATORY
MEDICAL RESEARCH INSTITUTE OF CHEMICAL DEFENSE
MEDICAL R&D COMMAND
MEDICAL RESEARCH INSTITUTE OF INFECTIOUS DISEASES
MISSILE R&D COMMAND
MOBILITY EQUIPMENT R&D COMMAND
NATICK R&D COMMAND
NIGHT VISION & ELECTRO-OPTICS LABORATORY
RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE
SIGNALS WARFARE LABORATORY
TANK-AUTOMOTIVE R&D COMMAND
WALTER REED ARMY INSTITUTE OF RESEARCH

TABLE A-4

PARTICIPATING INDUSTRY LABORATORIES

ALUMINUM COMPANY OF AMERICA
AMERICAN CAN COMPANY
AMERICAN TELEPHONE AND TELEGRAPH
ATLANTIC RICHFIELD COMPANY
B COMPANY
C COMPANY
CELANESE CHEMICAL RESEARCH COMPANY
CITIES SERVICE COMPANY
CORNING GLASS WORKS
D COMPANY
EXXON CHEMICALS AMERICA
F COMPANY
GENERAL MILLS, JAMES FORD BELL TECHNICAL CENTER
HUGHES AIRCRAFT COMPANY
I COMPANY
J COMPANY
KAISER ALUMINUM AND CHEMICAL COMPANY
PHILLIPS PETROLEUM COMPANY
STRATEGIC PLANNING INSTITUTE
UNION PACIFIC RAILROAD
UNITED STATES STEEL

APPENDIX B

DATA COLLECTION INSTRUMENT

TELEPHONE INTERVIEW QUESTIONNAIRE

ORGANIZATION ______________________________
NAME ______________________________
POSITION TITLE ______________________________
LABORATORY MANAGEMENT LEVEL ______________________________

Q1. Are you aware of any internal or external productivity measurement studies that have been conducted in your laboratory since 1970? Are there currently any internal or external studies in progress?

Q2. PRODUCTIVITY CLASSIFICATION

a. Is your laboratory's productivity determined subjectively, by objective indicators, both subjectively and objectively, or not at all?

b. How does your laboratory determine individual researcher productivity?

Q3. LABORATORY PRODUCTIVITY INDICATORS/DETERMINATION

a. What objective productivity indicators (criteria, standard, formula) are used in your laboratory?

b. Is your laboratory's productivity subjectively determined by the laboratory director (commander), division managers, or at each management level? What are the subjective criteria?

Q4. This question concerns the sources of new R&D projects. How are the specific new projects (approaches) selected? Is there a primary management level for project selection? Do you rely on the recommendation of your technical and professional personnel, and user and industry? Do you normally use special committees or consultants for project selection?

Q5. This question concerns the utility of productivity information. Is your laboratory's productivity compared against itself as a function of time or against other laboratories? Is laboratory productivity used to improve individual motivation? Does your laboratory use some form of the ratio of accomplishments/annual cost? Other purposes?

Q6. Is laboratory effectiveness (performing laboratory mission) and efficiency (output/input ratios) specifically determined? Are there other terms used as components of productivity?

Q7. As I stated in my introduction, this information is to be used in tabled form such that your responses cannot be correlated with you or your laboratory. Do I have your permission to list your company (laboratory) as a participant company (laboratory)? May I quote your responses? (if needed)?

Q8. Would you like to be included on the distribution list for this thesis? Formal Address?

APPENDIX C

CHRONOLOGICALLY TABLED LITERATURE

TABLE C-1

THEORETICAL LITERATURE REVIEW

MONTH YEAR	AUTHOR(S) TITLE.	DATA COLLECTION METHODOLOGY	STATISTICAL ANALYSIS	PRODUCTIVITY MEASUREMENT CATEGORY	THRUST
DEC 1963	Gerald Gordon "The Problem of Assessing Scientific Accomplishments: A Potential Solution."	THE C	Yes	S	Report summaries and the panel technique are employed to evaluate scientific accomplishment against four criteria.
DEC 1965	Martin M. Broadwell. "The Relationship Between the Engineer's Productivity, Satisfaction and Ability, or: $P_E = f(DS) + A$."	THE M	-	S	Satisfaction and ability effect output significantly.
1965	Ben Ami Lipetz. The Measurement of Efficiency of Scientific Research.	THE	P	O	Objective measures. Objective research efficiency.
1968	Daniel B. Roman. Research and Development Management: The Economics and Administration of Technology. Chapter 16.	THE	-	S O	Individual appraisal plus group performance equals organization's achievement.
SEP 1972	Robert M. Newburn, "Measuring Productivity in Organizations with Unquantifiable End-Products."	THE	-	S O	Quantification of functions. Work sampling. Performance appraisal.
MAY 1973	D. W. Collier, and R. E. Gee. "A Simple Approach to Post-Evaluation of Research."	THE	-	O	Performance vs. Objectives. Worth of R&D results.

KEY: C = Cases; Co = Complete; F = Field; G = Government; I = Industry; In = Interview; LR = Literature Review; M = Model; N = None; O = Objective; P = Percentage; S = Subjective SD = Standard Deviation; Su = Survey; U = University.

TABLE C-1 (Cont'd)

THEORETICAL LITERATURE REVIEW

MONTH YEAR	AUTHOR(S) TITLE.	DATA COLLECTION METHODOLOGY	STATISTICAL ANALYSIS	PRODUCTIVITY MEASUREMENT CATEGORY	THRUST
MAR 1977	Donald W. Collier. "Measuring the Performance of R&D Departments."	THE C	-	S O	Interdependent three-step process to measure R&D performance. Return-on-research (ROR) Index. Meeting predetermined objectives. Value of business opportunities generated by completed projects.
APR 1977	James E. Seitz. "Productivity: Patterns and Perspectives."	THE	P	S O	Each company develop its own measurement model. Productivity measurement and improvement.
MAY 1978	Richard E. Faust. "Emerging Challenges for the Research Scientist."	THE	N	S	Scientist assessment of utility of biomedical knowledge and potential rewards.
1978	Paul Mali. "Improving Total Productivity."	THE	P	O S	Measurement of productivity by ratios, total factor productivity, MBO, checklist indicators, audits.
SPRING 1979	Zvi Griliches. "Issues in Assessing the Contribution of Research and Development to Productivity Growth."	THE LR	M	O	Production function approach to estimate returns on R&D. Measurement of R&D output.
OCT 1980	Jack Hamelink, and Jerry Hamelink. "A Numeric Plan for Performance Appraisal."	THE	M	O	Actual performance (AP) less Performance standard (PS) = + (Above standard (AS)) or = 0 (Standard (S)) or = - (Below Standard (BS)).
1980	Delmar W. Karger, and Robert G. Murdick. <u>Managing Engineering and Research</u>. Chapter 13.	THE	P M	S O	General management approaches, indexes, individual, process. Inputs and outputs.

KEY: C = Cases; Co = Complete; F = Field; G = Government; I = Industry; In = Interview; LR = Literature Review; M = Model; N = None; O = Objective; P = Percentage; S = Subjective SD = Standard Deviation; Su = Survey; U = University.

TABLE C-2

EMPIRICAL LITERATURE REVIEW

MONTH YEAR	AUTHOR(S) TITLE.	DATA COLLECTION METHODOLOGY	PRODUCTIVITY MEASUREMENT CATEGORY	STATISTICAL ANALYSIS	SUBJECT CATEGORY	SAMPLE
1959	James R. Quinn. Yardsticks for Industrial Research.	In LR	S O	N	I	58 executives
1961	Calvin W. Taylor and others. "Explorations in the Measurement and Prediction of Contributions of One Sample of Scientists."	Su In	S O	Co	G	15 laboratories 215 scientists
JUN 1963	Cecil J. Mullins. "Predictions of Creativity in a Sample of Research Scientists."	Su	S O	Co	G	131 research scientists
1964	Raymond Villers. Research and Development: Planning and Control.	In	S O	P M	I	34 companies 269 individuals
1965	Robert E. Seiler. Improving the Effectiveness of Research and Development.	Su In	S O	P	I	116 companies
MAR 1966	Bernice T. Eidusun. "Productivity Rate in Research Scientists."	C	O	SD	I U	39 research scientists

KEY: C = Cases; Co = Complete; F = Field; G = Government; I = Industry; In = Interview; LR = Literature Review; M = Models; N = None; O = Objective; P = Percentage; S = Subjective; SD = Standard Deviation; Su = Survey; U = University.

TABLE 2 *(Cont'd)*

EMPIRICAL LITERATURE REVIEW

MONTH YEAR	AUTHOR(S) TITLE.	DATA COLLECTION METHODOLOGY	PRODUCTIVITY MEASUREMENT CATEGORY	STATISTICAL ANALYSIS	SUBJECT CATEGORY	SAMPLE
JUN 1966	John S. Burgess. "The Evaluation of a Government-Sponsored Research and Development Program."	C	S O	P	G	Compares industry and Government R&D laboratory evaluation yardsticks.
JL 1966	Lazarus Lebanoff. "Total Evaluation for Management Purposes of Engineering and Scientific Tasks."	C	S O	Co	G	Air Proving Ground Center (APGC)
1968	Edwin Mansfield. <u>Industrial Research and Technological Innovation: An Economic Analysis</u>.	Su In	S O	Co M	I	35 companies in five industries
FEB 1969	George F. Farris. "Some Antecedents and Consequences of Scientific Performance."	Su	S	Co	I	151 engineers
FEB 1969	Raymond W. Harrold. "An Evaluation of Measurable Charactertics Within Army Laboratories."	Su In	S O	Co	G	15 Army Laboratories

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TABLE C-2 (Cont'd)

EMPIRICAL LITERATURE REVIEW

MONTH YEAR	AUTHOR(S) TITLE.	DATA COLLECTION METHODOLOGY	PRODUCTIVITY MEASUREMENT CATEGORY	STATISTICAL ANALYSIS	SUBJECT CATEGORY	SAMPLE
APR 1969	George F. Farris. "Organizational Factors and Individual Performance."	Su	S	Co	I	151 engineers
FEB 1970	Stephen C. Hill. "A Natural Experiment on the Influence of Leadership Behavior Patterns on Scientific Productivity."	F Su	S O	P	G	25 scientists
DEC 1970	Michael J. Stahl. "An Exploratory Study of Organizational Environments that Influence the Creativity Scientists and Engineers in Air Force Research and Development Laboratories."	Su	S	Co	G	70 scientists
APR 1971	Richard Whitley and Penelope A. Frost. "The Measurement of Performance in Research."	LR	S O	N	-	79 references
FEB 1972	Edward M. Glass. "Methods of Evaluating R&D Organizations."	Su In C	S O	P M	G	DoD R&D Laboratories

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MAY 1972	Harry F. Vincent, and Abbas Mirakhor. "Relationship Between Productivity, Satisfaction, Ability, Age, and Salary in a Military R&D Organization."	Su	S O	Co	G	94 scientists and engineers
OCT 1972	Frank M. Andrews, and George F. Farris. "Time Pressure and Performance of Scientists and Engineers: A Five-Year Panel Study."	Su	S	Co	G	118 scientists
JAN 1973	Shirley A. Edwards, and Michael W. McCarrey. "Measuring the Performance of Researchers."	LR	S O	N	G I	52 references
JUN 1973	Michael W. McCarrey, and Shirley A. Edwards. "Organizational Climate Conditions for Effective Research Scientist Role Performance."	In	S O	Co	G	72 research biologists in four Canadian Government Laboratories

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JUL 1973	W. R. O'Brien "Effectiveness Evaluation in Military R&D Establishments."	C In	S O	Co M	G	23 teams 35 aircraft types 5 aircraft models 812 scientists engineers
JUN 1974	Frank Harrison. "The Management of Scientists: Determinants of Perceived Role Performance."	Su	S	Co	I	95 scientists in three research laboratories
APR 1975	Raphael Katzen. "Measuring the Productivity of Engineers."	C	S C	P	I	11 scientists
JUL 1976	Joseph G. Ferguson. "Applying the Key Work Objectives Approach to R&D--A Case Example."	C	O	N	I	Erling Riss Research Laboratories (ERRL)
SEP 1976	J. M. Whelan. "Project Profile Reports Measure R&D Effectiveness."	Su	S O	N	I	Union Carbide

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LR = Literature Review; M = Models; N = None; O = Objective; P = Percentage;
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DEC 1976	Michael C. Koser, 1 Lt., USAF. "Quantitative Scientist/Engineer Productivity and Some Associated Individual and Organizational Variables."	Su	O	Co	G	AFAL 135 scientists/engineers
DEC 1976	Arthur E. Stevens, Capt. USAF. "*Rewards in Air Force R&D*: An Analysis of Desirability, Perception and Association with Productivity of Scientists/Engineers."	Su	O	Co	G	278 scientists/engineers
1976	Michael J. Stahl. "Innovation and Productivity in Research and Development: Some Associated Individual and Organizational Variables."	Su	S O	Co	G	3 Air Force Laboratories 154 civilian and military scientists.

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JAN 1977	Michael J. Stahl and Joseph A. Steger. "Measuring Innovations and Productivity--A Peer Rating Approach.	Su	S O	Co	G	3 Air Force Laboratories 154 civilian and military scientists
FEB 1977	Michael J. Stahl, and Joseph A. Steger. "Innovation and Productivity in R&D; Associated Individual and Organizational Variables."	Su	S O	Co	G	3 Air Force Laboratories 154 civilian and military scientists
JUN 1977	A. P. Bakalkan, and N. V. Pitak. "Scientific Achievements Lead to Higher Production."	-	O	N	G	194 projects
SEP 1977	Larry J. Corbin. "Productivity and Job Satisfaction in Research and Development: Associated Individual and Supervisory Variables."	Su	O	Co	G	AFFDL 326 scientists/ engineers
OCT 1977	Russell C. Coile. "A Bibliometric Examination of the Square Root Theory of Scientific Publication Productivity."	LR	O	N	I G	Chemical abstracts authors

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MONTH YEAR	AUTHOR(S) TITLE.	DATA COLLECTION METHODOLOGY	PRODUCTIVITY MEASUREMENT CATEGORY	STATISTICAL ANALYSIS	SUBJECT CATEGORY	SAMPLE
JAN 1978	John G. Porter, Jr. "Post Audits - An Aid to Research Planning	C	S O	P	I	Mobile Research
FEB 1978	Michael J. Stahl, and Michael C. Koser. "Weighted Productivity in R&D: Some Associated Individual and Organizational Variables."	Su	S O	Co	G	135 scientists/ engineers
APR 1978	Michael J. Stahl, Capt., USAF. "Productivity in the Air Force Weapons Laboratory: Measurement and Prediction."	Su	O	Co	G	AFWL 135 scientists/ engineers
JUN 1978	Hughes Aircraft Company. <u>R&D Productivity: An Investigation of Ways to Improve Productivity in Technology Based Organizations.</u>"	In LR	O	N	G I	27 organizations 32 organizations
JAN 1979	Thomas A. DeCotiis, and Lee Dyer. "Defining and Measuring Project Performance."	Su In C	S O	Co M	1	20 R&D personnel

KEY: C = Cases; Co = Complete, F = Field; G = Government; I = Industry; In = Interview; LR = Literature Review; M = Models; N = None; O = Objective; P = Percentage; S = Subjective; SD = Standard Deviation; Su = Survey; U = University.

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MONTH YEAR	AUTHOR(S) TITLE.	DATA COLLECTION METHODOLOGY	PRODUCTIVITY MEASUREMENT CATEGORY	STATISTICAL ANALYSIS	SUBJECT CATEGORY	SAMPLE
SEP 1979	Roger D. Dekok, Major, USAF. "An Assessment of Team Development of the Air Force Flight Dynamics Laboratory."	Su C	O	Co	G	AFFDL 415 scientists and engineers
1979	National Research Council. Panel to Review Productivity Statistics. Measurement and Interpretation of Productivity.	Su LR	O	Co	G I	National level productivity
SEP 1980	William D. Rutley, Capt., USAF "An Assessment of Team Development at the Air Force Flight Dynamics Laboratory."	Su	O	Co	G	AFFDL 342 scientists and engineers

KEY: C = Cases; Co = Complete; F = Field; G = Government; I = Industry; In = Interview; LR = Literature Review; M = Models; N = None; O = Objective; P = Percentage; S = Subjective; SD = Standard Deviation; Su = Survey; U = University.

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